A COMPREHENSIVE ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY ASSESSMENT OF ROADWAY DRAINAGE SYSTEMS

BY

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THESIS

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ABSTRACT

The primary goal of roadway drainage systems is to quickly remove water from the roadway area to keep driving lanes safe; therefore, these systems are designed to quickly convey water that enters as runoff. However, this runoff carries pollutants (largely originating from vehicles) that travel through the drainage system and are often released to natural water bodies, thereby posing a risk to the local environment and public health over the life of the infrastructure's operation. At the same time, the system's construction and maintenance requires material inputs, equipment operation, and transportation that incur costs and contribute to global environmental impacts (e.g., climate change). In order to elucidate trade-offs across scales (spatial and temporal) and dimensions of sustainability (functional, environmental, economic), this research developed a comprehensive model of roadway drainage systems linking design decisions to sustainability metrics using fate and transport modeling, life cycle assessment (LCA), and life cycle costing (LCC) under uncertainty. This quantitative sustainable design framework is leveraged to characterize the implications of individual components and the system as a whole.

Results showed that drainage technologies that use concrete as a construction material (basins, culverts, storm sewers, and pipe underdrains) consistently had significantly larger environmental impacts than drainage components that did not use concrete (grass swales and bioswales). While the concrete consistently dominates environmental impacts, it does not consistently govern the total cost of the drainage system. Neither cost nor masses of materials were proven to be valid cut-off criteria; however, simply accounting for the concrete in the drainage system can account for the vast majority of climate change impacts (at least 95% for all sample projects evaluated).

The local water quality impacts of the operation and use phase (fate and transport of pollutants) did play a role in total life cycle impacts; however, these impacts were only noticeable relative to other life cycle phases for grass swales and bioswales, neither of which require concrete as a construction material. Although bioswales showed larger global environmental impacts as compared with grass swales, these impacts were insignificant compared to the impacts of storm sewers. The role of the operation and use phase in the total life cycle impacts of grass swales and bioswales combined with the observation that these total impacts are insignificant as compared with concrete drainage components such as storm sewers suggests that when comparing these technologies, global environmental impacts may not be relevant for decision-making. Rather, the potential local water quantity and water quality benefits of these technologies are better metrics for evaluating environmental sustainability.

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CHAPTER 1: INTRODUCTION

Conventional highway drainage systems are designed to cost-effectively manage runoff in a way that keeps the roadway safe for travel and protects the pavement with the goal of preserving existing hydrologic conditions. In order to protect the safety of vehicles on the road, runoff must be rapidly removed from the pavement surface. At the same time, the pavement must be protected from damage caused by poor drainage (e.g., cracking, frost action) which costs the United States billions of dollars in repair every year (Cedergren, 1994). Finally, these two objectives must be accomplished in a way that maintains existing drainage boundaries so that watersheds are not disrupted by the existence of the highway (Illinois State Toll Highway Authority, 2012). In order to cost-effectively accomplish these goals, highway drainage systems have traditionally been designed to remove water from the driving lines either by directing it to the outside shoulders or by infiltrating it through the pavement to an underdrain after which the water either infiltrates into the ground or discharges to surface water.

While water quantity has been the focus of highway drainage design in the past, the protection of local water quality is now being considered a part of drainage design. Highway runoff carries a variety of pollutants including particulate matter, heavy metals (e.g., copper, zinc, lead), and nutrients (e.g., ammonia, nitrate, phosphate) (Kayhanian et al., 2012). Due to the large amount of impervious area generating runoff that carries these pollutants, highways are major contributors to non-point source pollution (Ferreira et al., 2013) which travels through the drainage system and eventually deposits to surface water, groundwater, or soil. This contamination poses local environmental and health risks, as many stormwater pollutants exhibit toxicity (Pitt et al., 1995) and chronic and acute illnesses can be traced to stormwater runoff via exposure through drinking water, seafood, and recreation (Gaffield et al., 2003). The recognition of the potentially dangerous effects of stormwater runoff has prompted components of roadway drainage systems that were originally designed to attenuate flow (e.g., swales, basins) to now be considered in terms of their impacts on water quality (Ferreira & Stenstrom, 2013); therefore, the fate and transport of these pollutants through stormwater treatment devices such as swales (for example, Stagge et al., 2012) and basins (for example, Sébastian et al., 2015) has been the subject of ongoing research.

However, in addition to these local environmental impacts, the infrastructure of the drainage system contributes to global environmental impacts throughout the system's life cycle. The construction and maintenance of drainage system components such as storm sewers and culverts require materials (e.g., concrete), equipment operation (e.g., excavator), transportation (e.g., hauling of materials and equipment), and disposal (e.g., landfilling), all of which contribute to global environmental impacts such as climate change and stratospheric ozone depletion. While global environmental impacts have previously been quantified using life cycle assessment (LCA), the majority of stormwater related LCAs are focused on green infrastructure (Andrew & Vesely, 2008; Bozorg Chenani et al., 2015; De Sousa et al., 2012; Flynn & Traver, 2013; Ghimire et al., 2014; Kosareo & Ries, 2007; O'Sullivan et al., 2015; Rincón et al., 2014; Spatari et al., 2011; Vineyard et al., 2015; Wang et al., 2013) and only two of these studies incorporated the local water quality impacts associated with the operation and use phase (Flynn & Traver, 2013; Wang et al., 2013).

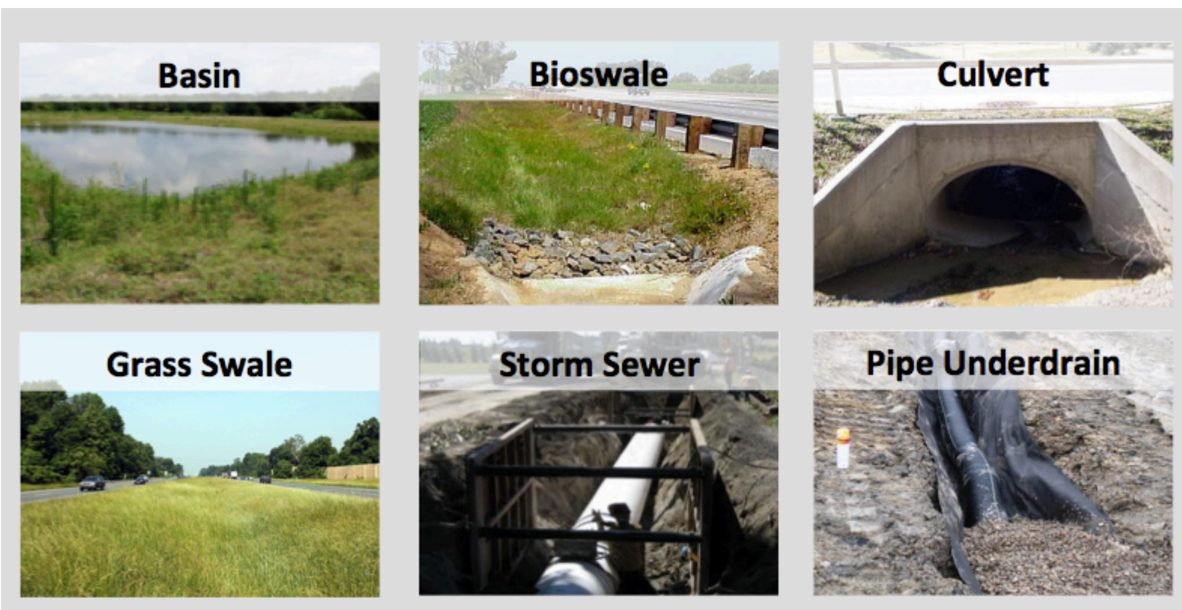
Local environmental impacts, global environmental impacts, and life cycle costs need to be considered simultaneously in order to comprehensively assess the environmental and economic sustainability of roadway drainage systems. In a review of the application of LCA to urban water systems, Loubet et al. emphasized the importance of considering direct water emissions for impact categories such as eutrophication and ecotoxicity (Loubet et al., 2014). In urban water systems, these impacts depend on pollutant concentrations, necessitating the inclusion of local considerations (Renou et al., 2008) within the LCA. Additionally, environmental impacts associated with system construction and maintenance activities (e.g., excavation) need to be included within the LCA (Loubet et al., 2014). Finally, environmental impacts quantified using LCA should be considered in conjunction with cost in order to make LCA applicable during decision-making (Reap et al., 2008b). The importance of each of these categories of impacts (global, local, cost) for decision-making necessitates the consideration of all three.

The overarching aim of this work is to elucidate the tensions and synergies among the environmental and economic impacts of drainage component and system design. Specific objectives are (1) to evaluate current roadway drainage systems for local impacts, global impacts, and cost (2) to pinpoint impacts and cost to specific life cycle stages, materials, and processes, and (3) to analyze trade-offs regarding life cycle assessment (LCA) vs. life cycle costing (LCC), local vs. global impacts, construction vs. operation, and conveyance element options in order to guide decision-making and future research. This is done by connecting design decisions (e.g., grass swale dimensions, storm sewer pipe diameter) to fate and transport modeling (local environmental impacts), LCA (global environmental impacts) and LCC (cost) in a Monte Carlo framework.

CHAPTER 2: BACKGROUND

2.1 Overview of Roadway Drainage Systems

This research considers six different components of roadway drainage systems: grass swales, bioswales, storm sewers, basins, pipe underdrains, and culverts (Figure 1). The first three components (grass swales, bioswales, and storm sewers) are linear conveyance elements that are used as the primary drainage system for a stretch of roadway. Grass swales are excavated, grass-lined open channels along the side of the road. Runoff enters the grass swales directly from the road and either infiltrates or discharges to surface water. Bioswales are similar to grass swales but include denser vegetation as well as a permeable subsurface layer in order to filter pollutants and promote infiltration. As with grass swales, roadway runoff enters bioswales directly from the road and either infiltrates or discharges to surface water. Storm sewers are closed, circular, underground pipes that run along the edge of the road. Runoff enters the storm sewer system through inlets that take the runoff into catch basins connecting to storm sewer pipes that ultimately discharge to surface water.



(*Basin:* Florida Water Associates; *Bioswale:* California Department of Transportation; *Culvert:* Huntsville, Alabama; *Grass Swale:* Maryland State Highway Administration; *Storm Sewer:* Tri-State Construction, Inc.; *Pipe Underdrain:* Newbury)

Figure 1: Overview of Drainage Components

In addition to these three major conveyance elements, roadway drainage systems can also include basins, pipe underdrains, and culverts. Basins are excavated ponds that can either store water only during a storm event (i.e., detention basin) or constantly maintain a permanent pool (i.e., retention basin). Basins are usually used when the volume of roadway runoff is large enough that having the runoff discharge directly to the natural water body would cause an undesirable increase in the flow to that receiving water; therefore, basins are used to store the runoff and slowly release it over time. Basins can also provide water quality benefits, particularly through settling of sediment. Pipe underdrains are small-perforated pipes, usually 6 or 8 inches in diameter, located beneath the road surface to capture water that infiltrates through the pavement. Underdrains help keep the pavement surface clear of water and also protect the pavement from deterioration caused by prolonged exposure to water. Finally, culverts are used to allow water to travel under the road surface in order to prevent the disruption of streams and other natural water bodies by roadway systems. Depending upon the flow of water, culverts can either be pipes or box culverts and typically require a headwall for structural stability and erosion prevention.

Roadway drainage system design is focused on cost-effective solutions for managing water quantity in a way that keeps the roadway safe for travel and protects the pavement. According to the Illinois Tollway's Drainage Design Manual, the designer of the roadway drainage system is responsible for providing a cost-effective method for handling the roadway's stormwater runoff in a way that follows the requirements of state drainage laws (Illinois State Toll Highway Authority, 2012). This design manual provides guidelines for drainage design, which are summarized as followed (Illinois State Toll Highway Authority, 2012):

1. Maintain existing drainage area boundaries.
2. Do not increase runoff discharge rates from existing conditions.
3. Keep off-site runoff away from Tollway drainage facilities when feasible and cost-effective.
4. Eliminate ponding of runoff from Tollway right of way (ROW) on adjacent properties.
5. Prevent erosion within Tollway ROW and adjacent properties that receive water from the ROW.
6. Prevent excess concentration of flows at a single location.
7. Verify existing permanent easements or obtain easements for affected adjacent properties.
8. Consider future maintenance of drainage systems to reduce potential future damage.
9. Incorporate field conditions to account for recorded pavement flooding or restricted outlets.
10. Consider providing emergency overflow routes to reduce extensive pavement flooding.

While reducing water quality impacts of stormwater is a concern, water quality management in the form of best management practices (BMPs) is encouraged only when it does not impact traffic safety and is cost-effective (Illinois State Toll Highway Authority, 2012) and is mainly centered around the management of erosion and sediment (Illinois State Toll Highway Authority, 2013a). For example, the Drainage Design Manual states that dry detention basins are preferred due to traffic safety and maintenance considerations; however, because of the potential water quality benefits, a wet basin can be used if it is cost-effective and does not cause a traffic hazard or is shielded by a guardrail (Illinois State Toll Highway Authority, 2012).

2.2 Local Environmental Impacts

2.2.1 Sources of Roadway Runoff Pollutants

In a review of the quality of highway runoff, Kayhanian et al. divided pollutants into three categories: conventional [total suspended solids (TSS), total dissolved solids (TDS), dissolved organic carbon (DOC), total organic carbon (TOC), chemical oxygen demand (COD), biochemical oxygen demand (BOD), oil and grease (O&G), hardness, and pH], metals [aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), nickel (Ni), and zinc (Zn)], and nutrients [nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), ammonia (NH_3), total Kjeldahl nitrogen (TKN), phosphate (PO_4^{3-}) and total phosphorus (Total P)] (Kayhanian et al., 2012). Many of these pollutants are a product of the roadway itself or vehicles (Ozaki et al., 2004); however, stormwater infrastructure installation and rehabilitation can also contribute to the degradation of stormwater quality (Tabor et al., 2014).

The presence of metals in highway runoff raises concern due to their toxicity and inability to be destroyed in nature (Davis et al., 2001). While the transition to unleaded gasoline has shifted attention away from roadway heavy metal deposition, many heavy metals (including lead) are still of concern in roadway runoff (Ozaki et al., 2004). These metals can be deposited either directly from vehicles or indirectly where they are first emitted to the atmosphere and later deposited (Gunawardena et al.. Metals such as copper, zinc, lead, and cadmium can be found in vehicle brake pad material and tires; therefore, as the pads and tires wear, these metals can be transported in roadway runoff (Davis et al., 2001). Other sources of metals include paint markings on pavement, diesel soot, and wearing of pavement (Ozaki et al., 2004).

Leaching of pavement materials into soil and groundwater has also been previously investigated as a source of pollutants (Birgisdóttir et al., 2007; Birgisdóttir et al., 2006). For example, industrial waste is often used in road construction as a filling material; however, this recycled waste can carry pollutants (e.g., metals, salts) which can then get transferred to soil and groundwater (Schwab et al., 2014). Despite these potential impacts, it is generally agreed upon that the sources of contamination in runoff are the results of vehicles rather than the materials of the pavement (Santero et al., 2011b).

2.2.2 Variability of Roadway Runoff Pollutant Concentrations

The concentrations of pollutants in highway runoff are highly variable. This variability was highlighted by the Environmental Protection Agency's Nationwide Urban Runoff Program (NURP) which monitored the quality of urban runoff in 28 locations across the United States (US EPA, 1983). For example, as part of NURP, the EPA took roadway water quality samples at two locations on John Street in Champaign, IL and found a mean concentration of Cu of 83 μg/L at one location and 43 μg/L at the other. Figure 2 highlights the variability of concentrations for four selected pollutants using concentrations and their associated standard deviations from roadway water quality studies throughout the United States, including two nationwide studies conducted by the EPA (NURP) and the Federal Highway Administration.

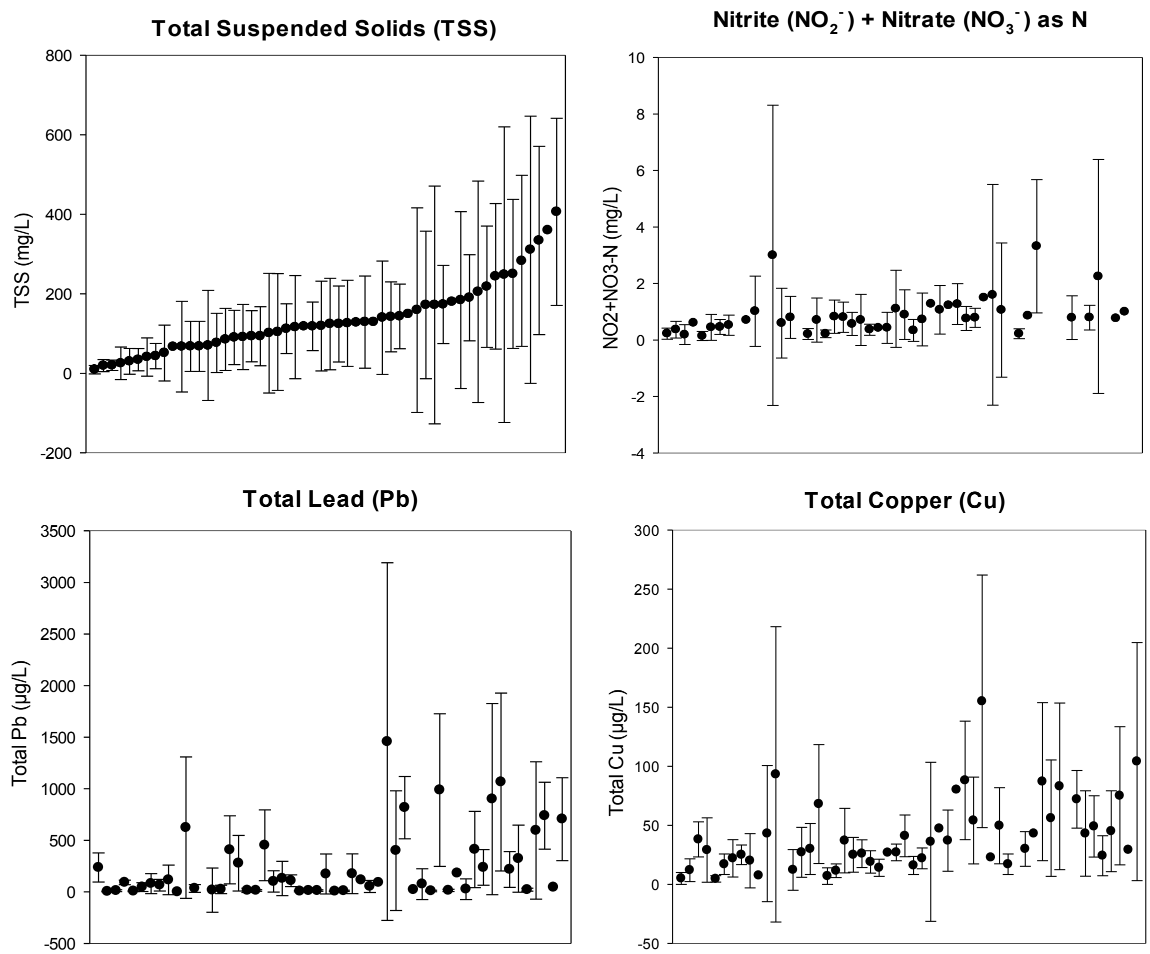


Figure 2: Variability of Concentrations of Pollutants in Highway Runoff

(references for studies included in Figure 2: Barrett et al., 1998; Barrett et al., 2006; Han et al., 2006; Kayhanian et al., 2003; Kayhanian et al., 2007; Lau et al., 2009; Li & Barrett, 2008; US EPA, 1983; US FHWA, 1990; Wu et al. , 1998)

Many of the proposed explanations for this variability focus on either the temporal or spatial differences among pollutant sources. Temporally, sources of pollutants can be temporary, seasonal, accidental, or chronic (Legret & Pagotto, 1999). Additionally, pollutant loadings can exhibit the first flush phenomenon where the concentrations of pollutants are higher during the beginning of a storm event (Flint & Davis, 2007; Han et al., 2006); this phenomenon can often be seen by plotting pollutant concentrations vs. time, known as a pollutograph (Kayhanian et al., 2012). Furthermore, when there are long periods of time between rain events, pollutants can build up on the roadway surface, strengthening the first flush; therefore, the number of dry days before a storm event (i.e., antecedent dry period) can also influence pollutant concentrations (Li & Barrett, 2008; Murphy et al. , 2015).

In addition to temporal differences, spatial differences among pollutant sources can also account for some of the variation of pollutant concentrations. A commonly discussed spatial variation associated with pollutant concentrations is a road's traffic volume, often quantified as annual average daily traffic (AADT), as many pollutants are associated with vehicles (Kayhanian et al., 2003). Other previously considered spatial variations include pavement type (Pagotto et al., 2000), winter maintenance treatment processes (Fitch et al., 2013), as well as local environmental policies (e.g., outlawing of leaded gasoline) (Ozaki et al., 2004).

Based on the existing understanding of these temporal and spatial influences on roadway runoff pollutant concentrations, work has been done with regression and modeling to try and predict concentrations from site-specific parameters. Irish et al. performed regression in relation to variables such as flow, duration, intensity, antecedent dry period duration, and average number of vehicles using the highway during a storm event (Irish et al., 1998). While this regression provided good predictions, some of the variables are dependent (e.g., flow and intensity), therefore potentially biasing the R^2 values of the results (Gupta, 2000). Similarly, Kayhanian et al. performed linear regression in relation to AADT and found no direct linear correlation but multiple regression analysis showed that AADT does play a role along with other watershed and pollutant characteristics (Kayhanian et al., 2003). Finally, even when regression analyses are successful, they are often site-specific, limiting their applicability to other locations (Murphy et al., 2015).

Others have developed pollutant build-up and wash-off models (Kim et al., 2005; Sharifi et al., 2014) after pointing out that regression analyses fail to capture the physical and chemical processes associated with pollutant concentrations (Sharifi et al., 2014). However, in the case of suspended solids for example, Sage et al. questioned using accumulation and wash-off models and reported that these fluctuations in concentrations during a rain event may not be relevant and simple event mean concentrations (EMCs) are sufficient, since pollutant loadings can mostly be explained by runoff volumes (Sage et al., 2015).

2.2.3 Pollutant Removal through Best Management Practices

Stormwater best management practices (BMPs) are used to mitigate the water quantity and water quality impacts of stormwater on the receiving environment. BMPs can be structural (e.g., swales, filter strips, rain gardens) or nonstructural (e.g., street sweeping, public education and outreach) (US EPA, 1999). For highway runoff, commonly implemented structural BMPs include swales (grass swales and bioswales) and basins (detention and retention). For both swales and basins, the primary treatment mechanism is sedimentation (Maniquiz-Redillas et al., 2014; Winston et al., 2012). Because many stormwater pollutants (e.g., nutrients, metals) adsorb to sediment, removal of TSS through sedimentation can potentially remove many more associated pollutants (Maniquiz-Redillas et al., 2014) and attention has been given to considering particle size distribution when assessing removal efficiency (Ferreira et al., 2013; Ferreira & Stenstrom, 2013). In addition to sedimentation, swales can achieve pollutant removal through filtration (Kayhanian et al., 2012) and retention basins can achieve removal through biodegradation, adsorption, chemical precipitation, and plant uptake (Wang et al., 2004).

The treatment effectiveness of swales and basins have been extensively studied both in terms of experimentation (Andrés-Valeri et al., 2014; Barrett et al., 1998; Bentzen & Larsen, 2009; Fletcher et al., 2002; Lucke et al., 2014; Maniquiz-Redillas et al., 2014; Sébastian et al., 2015; Stagge et al., 2012; Winston et al., 2012; Yousef et al., 1987; Yu et al., 2001) and modeling (Deletic, 2001; Fletcher et al., 2002; Maniquiz-Redillas et al., 2014; Wang et al., 2004; Wong et al., 2006). Just as the concentrations of pollutants in roadway runoff are variable, so are the removal rates of the pollutants as they travel through BMPs. For example, TSS removal through grass swales has been shown to vary anywhere from negative removal to close to 100% (Bäckström, 2002). There are many factors that contribute to the removal efficiency of a BMP, including length, infiltration rate, and vegetation characteristics for a swale (Bäckström, 2002) and surface area and storage volume for a basin (Maniquiz-Redillas et al., 2014).

Because of the variability of these factors, removal efficiency is often considered to be site-specific (Bäckström, 2003). To try and better understand the variable effectiveness of BMPs, Urbonas et al. recommended a set of parameters that studies should consistently report (Urbonas, 1995) and eventually the International Stormwater BMP Database was developed in order to collectively present existing removal efficiency data (Strecker et al., 2001). However, the BMP database excludes some information about design, therefore making it difficult to draw conclusions about treatment effectiveness (Ferreira & Stenstrom, 2013). Moreover, Barrett et al. warns that studies included in this database are included because they were well documented and not necessarily because they were well-designed (Barrett, 2008). These challenges result in large uncertainty ranges for removal efficiencies through BMPs in addition to the uncertainty associated with the initial concentrations of pollutants in roadway runoff.

2.3 Global Environmental Impacts

In addition to the aforementioned local environmental impacts, there are also global environmental impacts associated with the drainage system's construction, maintenance, and end of life. These global environmental impacts can be quantified using life cycle assessment (LCA).

2.3.1 Overview of Life Cycle Assessment

LCA is a methodology used to quantify the environmental impacts of a system over the course of that system's lifespan, which includes multiple phases: construction (e.g., material acquisition, operation of equipment, transportation), operation and use (e.g., electricity, water quality), maintenance (e.g., material acquisition, operation of equipment), and end of life (e.g., landfilling, recycling). Using LCA, emissions to soil, air, and water are quantified throughout the entire life cycle of the system and are then converted to environmental impacts (e.g., climate change, eutrophication, acidification). Knowledge of these environmental impacts can help decision makers consider the environment when making choices related to the design and operation of the system being considered.

LCA includes four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Figure 3). During the goal and scope definition, the goal of the LCA, the functional unit, and the system boundaries are defined. The functional unit is a consistent reference metric used throughout the LCA in order to allow for fair comparison among different alternatives. The system boundaries describe what is included within the LCA; these boundaries could include material production, construction, operation and use, and end of life. Next, the life cycle inventory includes all of the inputs (e.g., materials, energy) and outputs (emissions to soil, air, and water) associated with the system being considered. After the inventory is complete, the life cycle impact assessment (LCIA) step converts the emissions and raw material demand into environmental impacts; these impacts can either be presented as midpoint indicators (e.g., climate change, ozone depletion, eutrophication) or as endpoint indicators (e.g., skin cancer, crop damage, immune-system suppression) (Bare, 2002). As LCA is an iterative process, the interpretation phase is ongoing and may result in updates to the goal and scope definition, as well as the inventory or impact assessment, throughout the process.

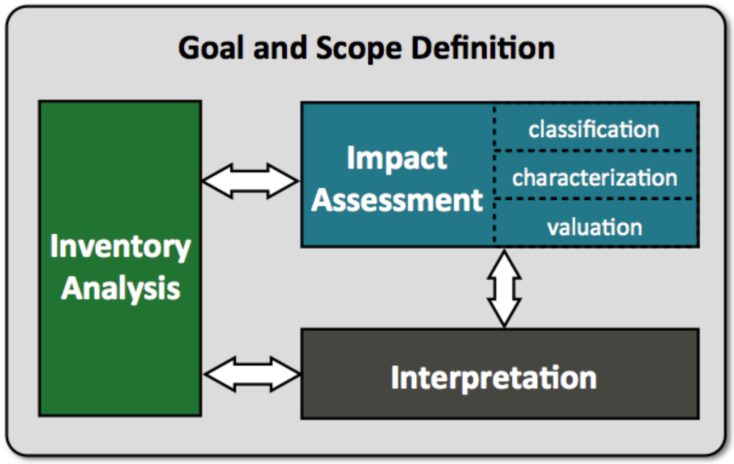


Figure 3: Overview of Life Cycle Assessment (LCA)

2.3.2 Application of LCA to Stormwater

LCA has been used extensively to evaluate wastewater treatment (Corominas et al., 2013) and also (although less frequently) drinking water treatment (for example, Choe et al., 2015; Choe et al., 2013); however, there are significantly fewer LCAs for stormwater management systems. Of these stormwater LCAs, the vast majority of them are LCAs of green infrastructure techniques and none to the author's knowledge are exclusively focused on roadway drainage systems.

Eleven papers were found to have used LCA to quantify the environmental impacts of green infrastructure. The technologies considered, type of functional unit, lifetime of the technology, included life cycle phases (CON: construction, O&M: operation and maintenance, EOL: end of life), and LCIA method for each of these eleven green infrastructure LCAs are summarized in Table 1.

Table 1: Summary of Green Infrastructure LCAs

Study	Technologies	*Functional Unit Type*	*Lifetime (years)*	*Included Phases*	*Inventory Databases*	*LCIA Method*
Andrew and Vesely, 2008	rain garden, sand filter	volume	50	CON: ✔ O&M: ✔ EOL: ✔	not specified	N/A
Bozorg Chenani et al., 2015	green roof	area	40	CON: - O&M: ✔ EOL: ✔	ecoinvent, Industry Data 2.0	CML
De Sousa et al., 2012	permeable pavement, street bump-outs, planters, rain gardens	area	50	CON: ✔ O&M: ✔ EOL: -	ecoinvent, US Input Output	IPCC
Flynn and Traver, 2013	rain garden	area	30	CON: ✔ O&M: ✔ EOL: ✔	USLCI	TRACI
Ghimire et al., 2014	rainwater harvesting	volume	system: 50 pumps: 15	CON: ✔ O&M: ✔ EOL: ✔	BEES, ecoinvent	TRACI
Kosareo and Ries, 2006	green roof	area	45	CON: ✔ O&M: ✔ EOL: ✔	SimaPro database (unspecified)	Impact 2002+
O'Sullivan et al., 2015	rain garden, sand filter	volume	30	CON: ✔ O&M: ✔ EOL: -	ecoinvent	Recipe
Rincón et al., 2014	green roof	area	50	CON: ✔ O&M: ✔ EOL: ✔	ecoinvent	Eco-Indicator
Spatari and Montalto, 2011	permeable pavement, street trees	area	N/A	CON: ✔ O&M: ✔ EOL: -	NPCC	N/A
Vineyard et al., 2015	rain garden	volume	35	CON: ✔ O&M: ✔ EOL: ✔	ecoinvent	TRACI
Wang et al., 2013	rain garden, green roof, permeable pavement	area	RG: 30, GR: 40 PP: 25	CON: ✔ O&M: ✔ EOL: -	ecoivent, US Input Output, USLCI	Recipe

Several of these studies showed the significance of construction within the total life cycle impacts of green infrastructure techniques. In a comparison of sand filters and rain gardens, O'Sullivan et al. highlighted the dominant effect of using concrete as a material (O'Sullivan et al., 2015) and Spatari et al. found the construction phase to play the biggest role in energy and greenhouse gas emissions when studying permeable pavement. Spatari et al., also pointed out the inability of LCA to capture many other benefits of green infrastructure (e.g., infiltration, retention, evapotranspiration, and carbon storage) (Spatari et al., 2011). Wang et al. considered local water quality in the context of LCA and found that the rain garden had the best ratio of water quality improvements to economic and climate costs but highlighted that there is a lot of uncertainty surrounding the stormwater runoff quality data (Wang et al., 2013).

Outside of green infrastructure, LCAs have been performed to specifically look at pipe materials (Du et al., 2013; Sanjuan-Delmás et al., 2014). Du et al. studied the global warming potential for six different materials of water and wastewater pipes and found that pipe material production was the dominant source of global warming potential while transportation had a negligible effect on the results, even when not considering the material production. The authors also pointed out that choosing a pipe material based on global warming potential would result in the same choice if the decision were based on cost, suggesting that using LCA for pipe materials may not enhance the decision-making process (Du et al., 2013).

Many LCAs have been conducted for roadways that are focused on pavement, as discussed in the two part review by Santero et al. (Santero et al., 2011a; Santero et al., 2011b). In general, these LCAs are focused on the pavement materials, including material extraction, production, transportation, and placement, with less of an emphasis on the operation and use of the roadway (e.g., traffic delay, rolling resistance, albedo, lighting) (Santero et al., 2011b). In a study focused on LCA of highways, Park et al. included drainage within the LCA; however, drainage was only considered for the construction phase and only energy consumption was evaluated (Park et al., 2003).

2.4 Need for Integration of Local and Global Impacts

Life cycle-based assessments of products and systems are becoming increasingly prevalent in research, policy, government, and industry through the application of life cycle assessment (Guinée et al., 2011) and environmental footprints (Fang & Heijungs, 2015; Ridoutt et al., 2015). Due to its focus on a product's entire life cycle, LCA will most likely continue to emerge as an important tool for sustainability assessments (Finnveden, 2000).

Despite its prevalence, LCA has limitations that make it challenging to be used for decision-making (Ayres, 1995; Finnveden, 2000; Reap et al., 2008a; Reap et al., 2008b). In particular, LCA focuses on global impacts (e.g., climate change, stratospheric ozone depletion), which makes it challenging to use for site-specific decision-making. The common U.S. life cycle impact assessment method, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), points out that while considering a specific location does not have an effect on certain impact categories (e.g., climate change, ozone depletion); it can influence the fate, transport, and potency associated with others (e.g., eutrophication, acidification) (Bare, 2011). Although the original version of TRACI included spatial variation at the state level (Bare, 2002; Norris, 2002); the second version focused solely on U.S. average characterization factors (Bare, 2011). Therefore, current LCIA methodologies must be modified in order to account for the locational differences in sensitivity of receiving environments (Kalbar et al., 2013). In response to this, developing methods to account for this spatial variation within the existing LCA framework has been the subject of ongoing research (Helmes et al., 2012; Humbert et al., 2009; Mutel & Hellweg, 2009; Pennington et al., 2005; Quinteiro et al., 2015; Roy, Deschênes, & Margni, 2012; Roy, et al., 2012).

Specifically focusing on LCAs for water systems, methods for addressing the appropriate temporal and spatial scales within LCA are still under development (Xue et al., 2015). LCAs often rely on theoretical data from open sources (Ayres, 1995); however, for impact categories such as eutrophication and ecotoxicity, impacts depend on concentrations of pollutants; therefore, there must be consideration of locality specific parameters (Renou et al., 2008). Roadway drainage systems impact both the local environment (e.g., fate and transport of pollutants) and the global environment (e.g., production of materials, operation of equipment). Therefore, the local impacts, which are site-specific and affected by the receiving environment, must be considered within the larger globally focused LCA in order to comprehensively assess the environmental sustainability of roadway drainage systems.

CHAPTER 3: METHODS, RESULTS, AND DISCUSSION

3.1 Methods

3.1.1 Overview

The system boundaries for the life cycle assessment (LCA) and life cycle costing (LCC) include construction, maintenance, operation and use, and end of life. Construction and maintenance phases are comprised of material production, operation of onsite equipment, and transportation of materials and equipment to the site. The operation and use phase includes the fate and transport of pollutants as they travel from the road through various drainage components. Six drainage components were considered as potential parts of the drainage system: (1) basin (dry or wet), (2) bioswale, (3) culvert, (4) grass swale, (5) storm sewer, and (6) pipe underdrain. LCA and LCC results are calculated for a lifetime of 60 years, after which major rehabilitation (e.g., storm sewer replacement, culvert rehabilitation) is usually required. LCA and LCC results are calculated from design decisions using the calculation structure shown in Figure 4.

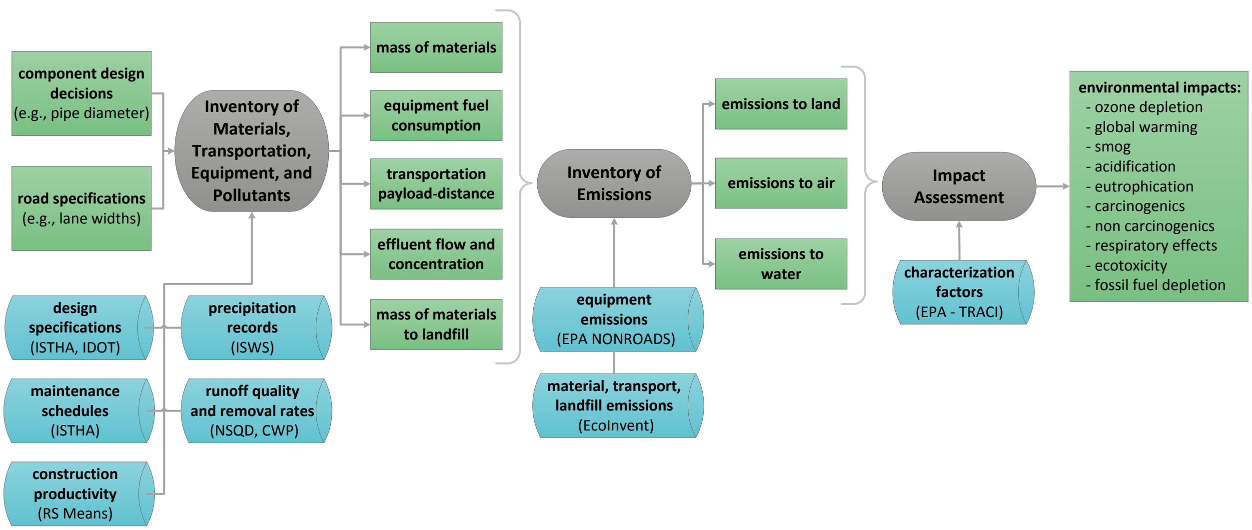


Figure 4: Overview of LCA Calculation Structure

3.1.2 Construction Materials and Equipment

Material and equipment requirements for each of the six drainage components were determined using design specifications from the Illinois Tollway's Drainage Design Manual (Illinois State Toll Highway Authority, 2012), Landscape Manual (Illinois State Toll Highway Authority, 2013a), Standard Drawings (Illinois State Toll Highway Authority, 2013b), and Standard Specifications (Illinois State Toll Highway Authority, 2013c), supplemented with manufacturer specifications or communication with the Illinois Tollway when necessary. Grass swales require material inputs of grass seed and fertilizer and equipment operation of an excavator, a hydroseed sprayer, and compactor. Optional inputs include an erosion blanket, requiring material inputs of polypropylene and straw and equipment requirements of a skid steer loader. Bioswales require seed, fertilizer, plug plants, sand, topsoil, and operation of an excavator, hydroseed sprayer, and wheel loader (see Appendix A for bioswale cross section). As with the grass swale, an optional erosion blanket can be included. Basins require grass seed and riprap as well as precast concrete, rebar, steel, and cast iron for the outlet structure (see Appendix A for outlet structure diagram). Equipment for basin construction and maintenance includes an excavator, hydroseed sprayer, skid steer loader, grader, and compactor. An optional erosion blanket can be included. Culverts require precast concrete and rebar for the culvert pipe and any headwalls. Equipment operation for a culvert includes an excavator and a compactor. Storm sewer materials include precast concrete and rebar for catch basins, storm sewer pipes, and manholes and cast iron for storm sewer inlets. Equipment includes an excavator, wheel loader, and compactor. If a curb and gutter is included, cast-in-place concrete and rebar are required for materials and a slipform paver and concrete mixer are required for equipment. Backfilling can either be done with sand or previously excavated material and is done using an excavator. Pipe underdrains require material inputs of HDPE for the pipe, polyester for the liner, precast concrete and rebar for the outlet headwalls, cast iron for the outlet grates, and sand as an optional backfill material. Required equipment for pipe underdrain construction includes a trencher and a compactor.

3.1.3 Maintenance Activities

The maintenance schedule for each drainage component was based on communication with the Illinois Tollway and includes: mowing of grass swales 3 times a year (requires a mower); mowing of bioswales yearly (requires a mower); herbicide application for grass swales and bioswales yearly (requires herbicide and hydroseed sprayer); seeding for grass swales, bioswales, and basins every 15 years (requires seed and hydroseed sprayer); fertilizing of grass swales and bioswales every 15 years (requires fertilizer and hydroseed sprayer); cleaning of storm sewers every 15 years (requires a vactor truck); grading of grass swales and bioswales every 15 years (requires a grader); and compacting of grass swales every 15 years (requires a compactor).

3.1.4 Material and Equipment Inventory

Material requirements for each of the six drainage components were calculated from design decisions using design specifications (Illinois State Toll Highway Authority, 2012, 2013a, 2013b, 2013c) and the inventory associated with each material was found in the ecoinvent v3.1 database included in SimaPro v8.0.4. Equipment required for construction and maintenance activities were matched to equipment in the EPA's NONROADS model (US EPA, 2008). Productivity rates for each construction and maintenance activity were obtained from RS Means (Babbitt, Charest, Elsmore, & Kuchta, 2014; Fortier, 2014) and used to calculate time of equipment operation. Fuel efficiency data for each equipment type came from the NONROADS model and was used to calculate fuel consumption. NONROADS was used to obtain equipment specific emissions per gallon of fuel for total hydrocarbons (both exhaust and crankcase), carbon monoxide, nitrogen oxides, carbon dioxide, sulfur dioxide, and particulate matter associated with combustion. These combustion emissions were combined with a US-EI process for diesel production in order to calculate the total emissions associated with equipment operation for each equipment type (see Appendix B for details). Emissions from transportation of materials and equipment were accounted for using an ecoinvent hauling truck process for an average transportation distance of 10 miles. A landfilling process in ecoinvent was used to account for disposal of storm sewers, culverts, underdrains, and basin outlet structures at the end of the 60-year lifetime. Grass swales and bioswales were assumed to stay in place with no disposal at the end of the system's lifetime.

3.1.5 Operation and Use

Flow from the road into the drainage system was calculated using the rational method, which involves an imperviousness coefficient, storm intensity, and drainage area. Hourly precipitation data for Chicago from the Illinois State Water Survey was used to calculate the intensity, precipitation depth, and storm duration of each storm for ten years of data (2004 – 2013). A rational method imperviousness coefficient of 0.9 was used for the pavement surface.

Initial concentrations of highway runoff were obtained from the National Stormwater Quality Database (NSQD) v4.02 (Pitt & Maestre, 2015) for database entries with a land use classification of 100% highways and/or freeways. Pollutants include total suspended solids (TSS), biochemical oxygen demand (BOD5), total dissolved solids (TDS), total arsenic (As), total cadmium (Cd), total chromium (Cr), total copper (Cu), total iron (Fe), total nickel (Ni), total lead (Pb), total zinc (Zn), nitrate (NO_3^- as N), ammonia (NH_3 as N), and orthophosphate (oPO_4^{3-} as P).

Treatment efficiency for grass swales, bioswales, and basins (both wet and dry) were quantified using percent removal data from the National Pollutant Removal Performance Database Version 3 (Center for Watershed Protection, 2007). Grass swales were considered to be open channels, bioswales were considered to be bioretention, and basins were considered to be dry ponds or wet ponds depending on whether or not they retained water. Removed TSS was assumed to settle out (no impacts); removed nutrients were assumed to settle or sorb (no impacts); removed BOD5 was assumed to be degraded (no impacts); removed TDS and metals were assumed to go to soil (applied characterization factors for emissions to soil).

3.1.6 Impact Assessment

Using the Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) v2.1 developed by the EPA (J. Bare, 2011), the life cycle inventory emissions were converted to ten midpoint impact categories: ozone depletion (kg CFC-11 eq), climate change (kg CO_2 eq), smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogenics (CTUh), noncarcinogenics (CTUh), respiratory effects (kg $PM_{2.5}$ eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). Material, transportation, and end of life impacts were converted using TRACI v2.1 within SimaPro v8.0.4. Equipment emissions from NONROADS were matched to emissions that were included in TRACI using EPA conversion factors for hydrocarbons (US EPA, 2010a) and particulate matter (US EPA, 2010b) (see Appendix B for details). Pollutants from the operation and use phase were converted to impacts using TRACI directly.

3.1.7 Life Cycle Costing

Construction and maintenance operations were summarized by 27 activities and matched to 2015 RS Means data for either heavy construction (Fortier, 2014) or site work and landscaping (Babbitt et al., 2014). These data were used to obtain costs broken down by materials, equipment, labor, total, and total including overhead and profit (see Appendix D for the 27 activities and associated productivity rates and costs). End of life costs were calculated using landfilling tipping fees from RS Means. Costs of future maintenance activities and landfilling were converted to present day prices using present worth analysis with a discount rate of 6.0%.

3.1.8 Uncertainty Analysis

Uncertainty analysis was conducted using Monte Carlo with Latin Hypercube Sampling for 1,000 simulations, implemented in Matlab. Uncertainty surrounding the rational method coefficient, transportation distance, interest rate, cost of construction and maintenance activities, and weight of equipment was described using triangular probability distributions (see Appendix C for distributions). Frequency of maintenance activities for seeding, fertilizing, and grading and compacting were varied together uniformly for a range of 10 to 25 years and storm sewer pipe cleaning was varied separately also uniformly for a range of 10 to 25 years.

Initial concentrations of pollutants in roadway runoff were varied using an empirical distribution with data from NSQD for entries with 100% land use classification of highways and/or freeways (Pitt &

Maestre, 2015). Entries that were below the detection limit were set at the limit and concentrations that were more than three standard deviations away from the next largest concentration were identified as outliers and removed from the dataset. Additionally, entries for Dulaney Valley Road and Pindell School Road in Maryland were identified as mistakes in the database and also removed from the dataset (A. Maestre, personal communication, June 24, 2015). Treatment efficiencies for grass swales, bioswales, and basins (both dry and wet) were varied according to the distributions presented in the National Pollutant Removal Performance Database (Center for Watershed Protection, 2007). Cumulative probability plots were constructed based on the quartile data provided and were used to identify most probable values in order to create triangular distributions for removal rates each pollutant (see Appendix C for details).

3.2 Results and Discussion

3.2.1 Impact and Cost of Drainage Technologies

LCA and LCC results were calculated for 10 sample sections of drainage systems along an interstate highway in the Midwest United States. Project 1 and Project 2 consisted of storm sewers and grass swales; Project 3 consisted of bioswales and grass swales; Project 4, Project 5, and Project 6 consisted of grass swales and a culvert; Project 7 consisted of storm sewers and a basin; Project 8 consisted of grass swales, bioswales, and a culvert; Project 9 consisted of storm sewers; Project 10 consisted of grass swales, a culvert, and a basin. All 10 projects included pipe underdrains below the pavement. For each project, impacts and cost were normalized to linear foot of drainage technology (for basins, impacts were normalized to entire length of project) to characterize the unit impacts and cost of each drainage technology (Figure 5, Figure 6).

Basins were shown to have the largest cost per linear foot of roadway due to the large amount of excavation required; however, relative climate change impacts associated with basin construction and maintenance were smaller than that of other drainage components. Excluding basins, culverts were shown to have the greatest total cost and total climate change impacts. This is due to the large amount concrete used for both the culvert pipe and headwalls. After culverts, storm sewers showed the largest climate change impacts. As with the culverts, storm sewer impacts are dominated by concrete that is used for the pipe, manholes, curb and gutter, and catch basins of the storm sewer system.

Bioswales showed larger climate change and cost impacts than grass swales (Figure 6) due to the additional materials (e.g., sand, topsoil) required as compared with grass swales. Pipe underdrains had larger relative climate change impacts than grass swales and bioswales for each project; however, their costs were smaller due to the low maintenance requirements of underdrains. Climate change impacts of pipe underdrains can be traced to the concrete headwalls used for the underdrain outlets.

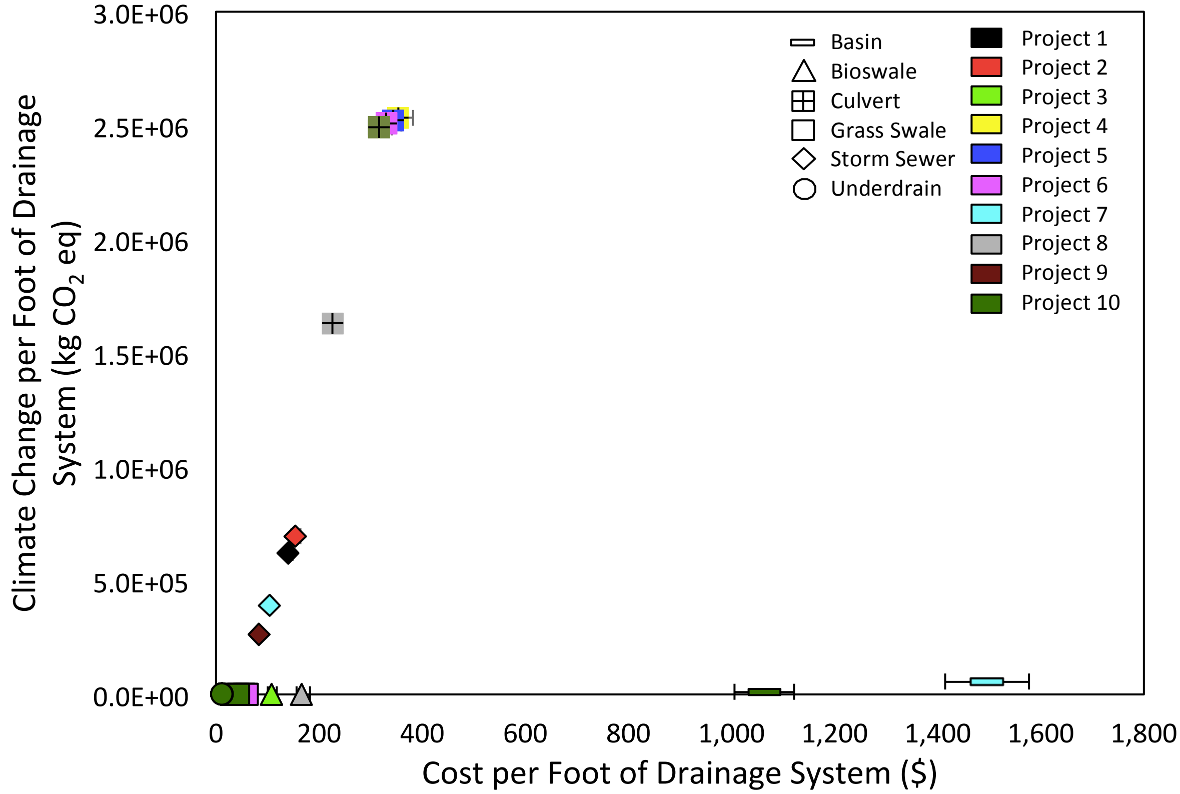


Figure 5: Cost vs. Climate Change for Sample Projects (All Components)

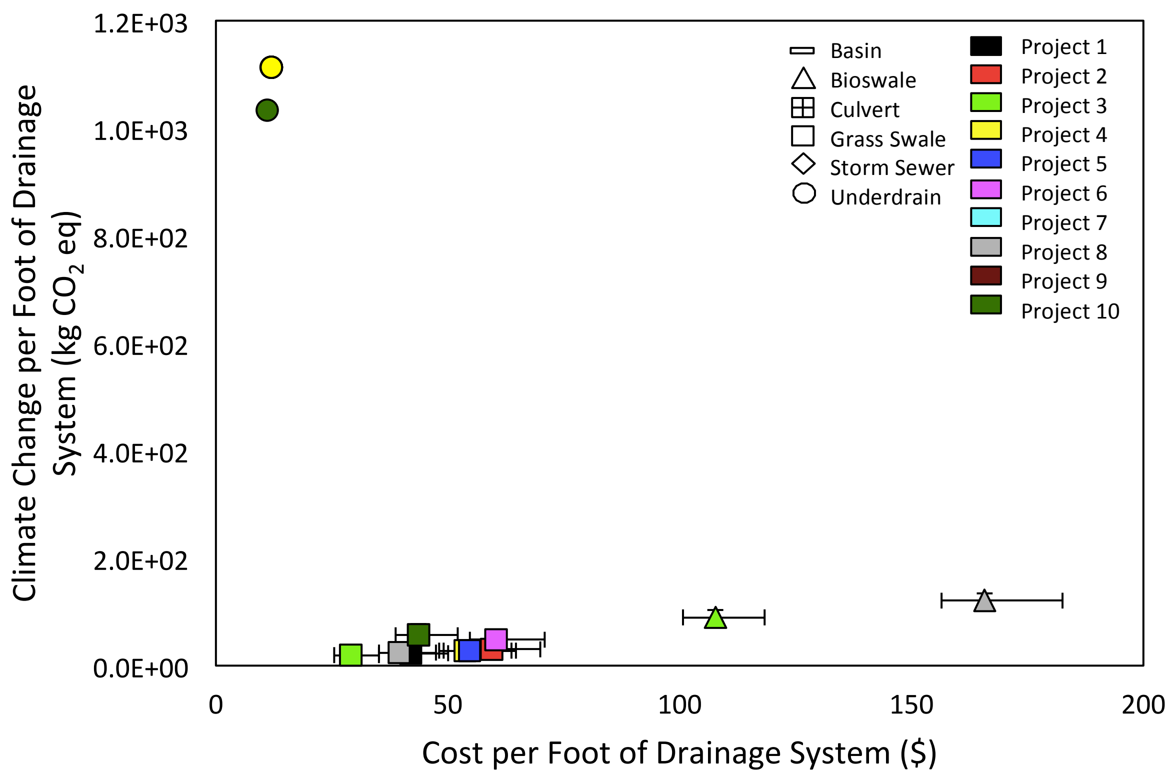


Figure 6: Cost vs. Climate Change for Sample Projects (Swales and Underdrains)

3.2.2 Evaluating Cost and Mass as a Cut-off Criteria for Drainage Projects

The cut-off criterion for an LCA indicates what inputs and outputs are included within the system boundary. According to ISO standards, a valid cut-off criterion can be based on mass, energy, or environmental significance (International Organization for Standardization, 2006). Cost is not listed as a valid cut-off criterion because it is possible that very inexpensive products could have significant environmental implications. If cost could consistently provide a good environmental cut-off, this would save time when conducting an LCA as the cost of systems is usually already known and is much simpler to account for rather than mass, energy, or environmental significance. Particularly for roadway drainage systems, the cost of materials is already known through a project's bid tabs; therefore, using cost as a cut-off criterion would make conducting an LCA a much simpler process.

In order to investigate the validity of using cost as a cut-off criterion for LCA, cumulative climate change vs. cumulative cost was plotted for each of the 10 sample projects (Figure 7). Each point in the figure corresponds to one of the 27 applicable construction and maintenance activities used for that sample project. The unit impacts for each of the 27 activities are summarized in Table 2. The percent contribution to total cost and total climate change impacts of each activity were calculated and activities were ranked from most expensive to least expensive.

This analysis made it clear that the vast majority of the climate change impacts for all of the ten projects are associated with the use of concrete. Concrete is used as a construction material for storm sewers (reinforced concrete pipe, manholes, curb and gutter, catch basins), culverts (reinforced concrete pipe, headwalls), basins (reinforced concrete pipe for basin outlet), and underdrains (headwalls for underdrain outlets). Reinforced concrete pipe causes the large jump from close to 0% to over 80% cumulative climate change impacts for all ten projects. For all projects except project 3, this leap is traced to reinforced concrete pipe used for storm sewers, culverts, or basins. For project 3, which did not include any of these three drainage components (storm sewers, culverts, or basins) the large jump is associated with the concrete used for the headwalls of the pipe underdrain outlets. Project 3 included a combination of grass swales and bioswales along with a pipe underdrain. The pipe underdrain is made out of HDPE; therefore, the only concrete used is for the headwalls of the outlet structures, which are assumed to occur every 500 feet along the pipe. However, this small amount of concrete accounted for over 95% of Project 3's climate change impacts. For many of the projects, there were activities with greater cost than the concrete related activities (e.g., excavation); however, these activities accounted for a small portion of the total climate change impacts.

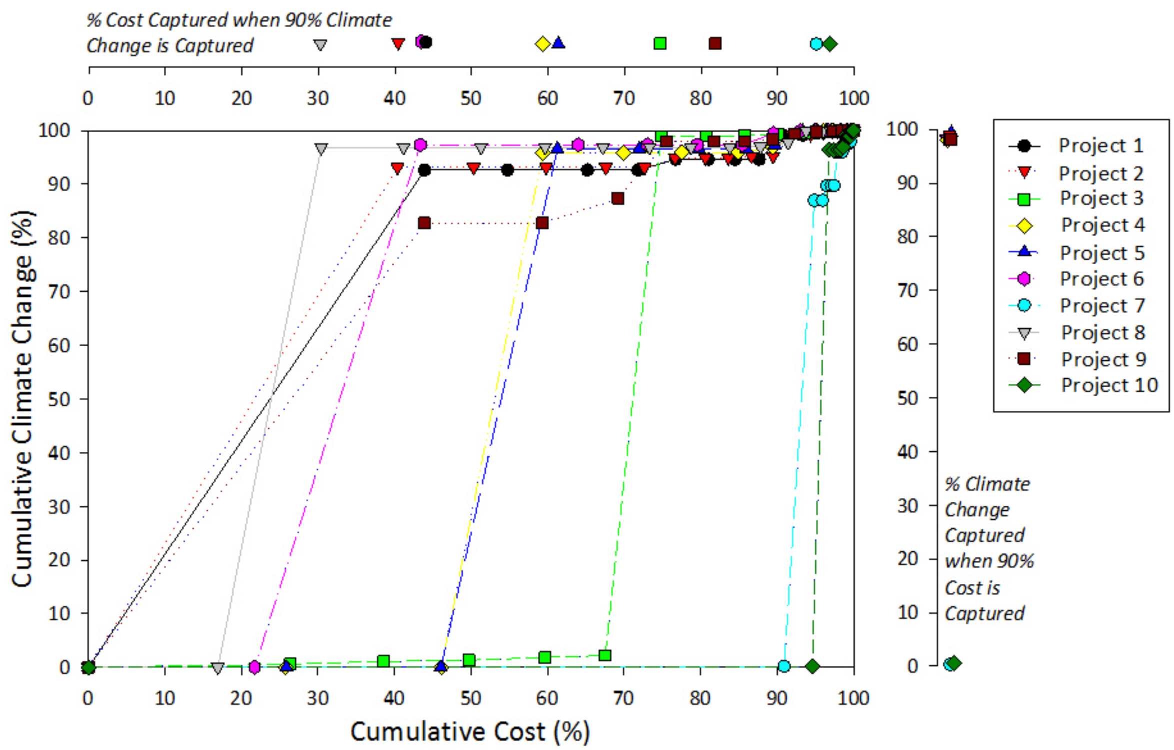


Figure 7: Cumulative Climate Change vs. Cumulative Cost of Construction and Maintenance Activities (activities ranked from most expensive to least expensive)

Due to the dominant effects of concrete on climate change impacts, mass was also investigated as a cut-off criterion for LCA. Cumulative mass vs. cumulative climate change impact was plotted for each of the 10 sample projects (Figure 8). Just as was true for cost, many of the projects included activities that had greater mass than the concrete related activities but that accounted for a small portion of the total climate change impacts. In particular, activities with sand or topsoil often had large relative mass with small relative climate change impacts. This can be seen clearly with Project 3 (Figure 8) that included grass swales, bioswales, and a pipe underdrain. For this project, the two greatest contributions to total mass of the project were topsoil and sand, which are both used for bioswales. However, as previously mentioned, the concrete headwalls for the underdrain outlet structures (which had the third largest mass for Project 3) dominated this project's climate change impacts.

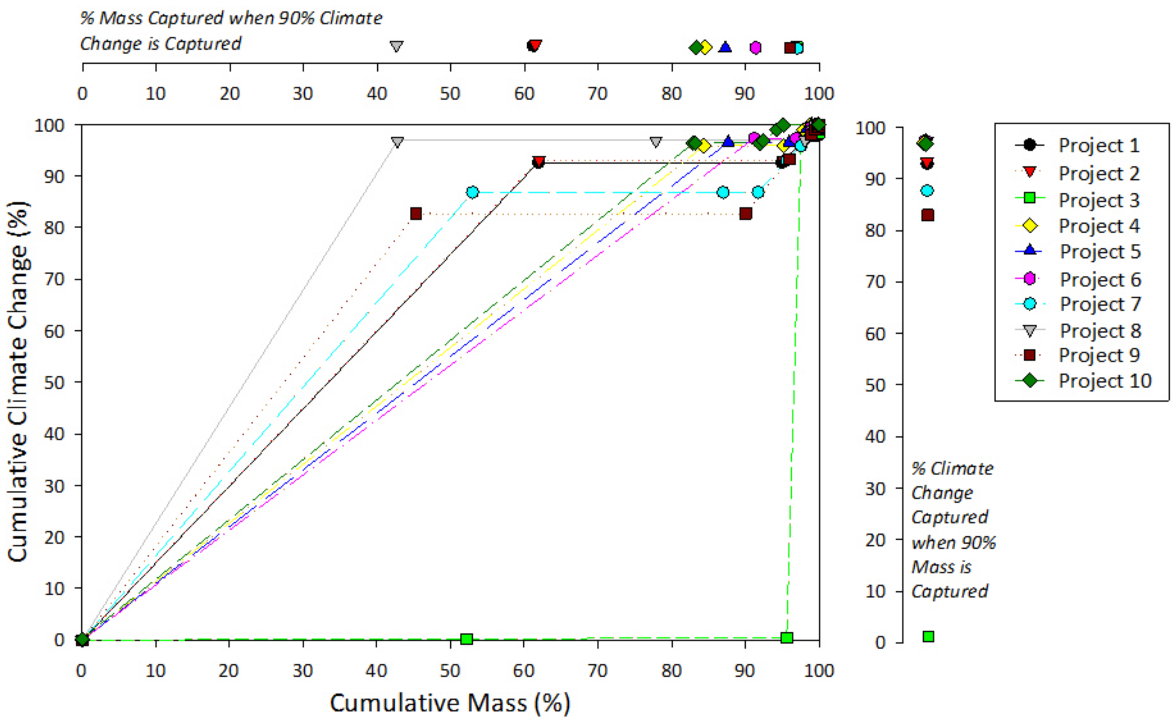


Figure 8: Cumulative Climate Change vs. Cumulative Mass of Construction and Maintenance Activities (activities ranked from largest mass to smallest mass)

These results suggest that neither cost nor mass provide a valid cut-off method when conducting an LCA of roadway drainage systems. However, for all 10 projects regardless of what drainage technologies are used, concrete consistently and significantly dominated total climate change impacts. Therefore, rather than using cost or mass as cut-off criteria, simply accounting for the concrete in the drainage system can account for the vast majority of climate change impacts (at least 95% for each of the 10 sample projects).

Table 2: Unit Impacts of Construction and Maintenance Activities

Activity	Unit	Ozone Depletion (kg CFC-11 eq)	Climate Change (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogenics (CTUh)	Non-carcinogenics (CTUh)	Respiratory Effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil Fuel Depletion (MJ surplus)
Excavating trench for storm sewer	BCY	1.2E-06	5.7E+00	3.6E-01	1.8E-02	3.7E-03	2.0E-09	8.6E-08	3.7E-02	7.2E-01	1.5E+01
Cleaning storm sewer pipe 12 IN	LF	5.2E-05	3.0E+02	5.7E+01	2.0E+00	2.3E-01	8.3E-08	3.6E-06	2.5E-01	3.0E+01	6.5E+02
15 IN	LF	6.5E-05	3.8E+02	7.2E+01	2.5E+00	2.9E-01	1.0E-07	4.5E-06	3.1E-01	3.8E+01	8.1E+02
18 IN	LF	7.8E-05	4.5E+02	8.6E+01	3.0E+00	3.5E-01	1.3E-07	5.4E-06	3.7E-01	4.5E+01	9.7E+02
24 IN	LF	1.0E-04	6.1E+02	1.1E+02	4.0E+00	4.7E-01	1.7E-07	7.2E-06	5.0E-01	6.1E+01	1.3E+03
30 IN	LF	1.3E-04	7.6E+02	1.4E+02	5.0E+00	5.9E-01	2.1E-07	9.0E-06	6.2E-01	7.6E+01	1.6E+03
36 IN	LF	1.6E-04	9.1E+02	1.7E+02	6.0E+00	7.0E-01	2.5E-07	1.1E-05	7.5E-01	9.1E+01	1.9E+03
42 IN	LF	1.8E-04	1.1E+03	2.0E+02	7.0E+00	8.2E-01	2.9E-07	1.3E-05	8.7E-01	1.1E+02	2.3E+03
48 IN	LF	2.1E-04	1.2E+03	2.3E+02	8.0E+00	9.4E-01	3.3E-07	1.4E-05	1.0E+00	1.2E+02	2.6E+03
60 IN	LF	2.6E-04	1.5E+03	2.9E+02	1.0E+01	1.2E+00	4.2E-07	1.8E-05	1.2E+00	1.5E+02	3.2E+03
Riprap	LCY	1.3E-06	3.0E+01	8.6E+00	2.8E-01	3.3E-02	1.9E-07	9.2E-07	3.7E-02	2.3E+01	6.1E+01
Basin grading	MSF	4.7E-06	2.2E+01	1.4E+00	6.9E-02	1.4E-02	7.6E-09	3.3E-07	1.3E-01	2.8E+00	5.9E+01
Swales grading	SY	1.8E-08	8.3E-02	5.1E-03	2.6E-04	5.3E-05	2.8E-11	1.2E-09	4.8E-04	1.0E-02	2.2E-01
Herbicide application	MSF	1.7E-07	4.8E-01	2.4E-02	2.3E-03	2.2E-03	2.2E-08	1.5E-07	3.4E-04	3.9E+00	1.4E+00
Mowing bioswales	MSF	1.5E-06	7.1E+00	4.4E-01	2.2E-02	4.5E-03	2.4E-09	1.1E-07	4.1E-02	8.8E-01	1.9E+01
Seeding and fertilizing	SY	2.9E-08	2.1E-01	1.2E-02	1.2E-03	7.3E-03	5.4E-09	1.2E-07	5.7E-04	1.2E+00	3.4E-01
Erosion blanket	SY	3.1E-08	2.6E-01	3.9E-02	1.7E-03	1.1E-03	4.3E-09	6.3E-08	3.2E-04	6.0E-01	6.0E-01
Excavation	BCY	1.8E-07	8.2E-01	5.2E-02	2.6E-03	5.3E-04	2.8E-10	1.2E-08	5.2E-03	1.0E-01	2.2E+00
Excavating Trench for Underdrain	CY	2.8E-06	1.6E+01	3.0E+00	1.0E-01	1.2E-02	4.5E-09	1.9E-07	1.0E-02	1.6E+00	3.5E+01
Backfilling with Sand	LCY	3.6E-06	4.1E+01	9.0E+00	3.2E-01	4.7E-02	7.6E-07	4.0E-06	1.9E-02	1.2E+02	8.0E+01

Table 2 (continued): Unit Impacts of Construction and Maintenance Activities

Activity		Unit	Ozone Depletion (kg CFC-11 eq)	Climate Change (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogenics (CTUh)	Non-carcinogenics (CTUh)	Respiratory Effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil Fuel Depletion (MJ surplus)
Compaction		ECY	2.1E-09	1.3E-02	2.6E-03	8.9E-05	1.0E-05	3.4E-12	1.5E-10	1.1E-05	1.2E-03	2.7E-02
Geotextile fabric		SY	1.2E-07	1.1E+00	5.9E-02	5.2E-03	5.0E-03	4.2E-08	1.7E-07	7.4E-04	6.7E+00	1.7E+00
Topsoil		SY	1.6E-07	1.2E+00	1.9E-01	6.8E-03	9.3E-04	7.9E-09	5.3E-08	4.3E-03	1.4E+00	2.8E+00
Curb and gutter		LF	1.8E-03	2.8E+04	1.6E+03	8.4E+01	3.0E+01	4.7E-04	3.0E-03	9.7E+00	7.1E+04	1.7E+04
Underdrain headwall		EACH	3.6E-02	5.5E+05	3.1E+04	1.7E+03	5.9E+02	9.4E-03	6.0E-02	1.9E+02	1.4E+06	3.4E+05
Reinforced concrete pipe (RCP)	12 IN	LF	7.9E-03	1.2E+05	6.9E+03	3.7E+02	1.3E+02	2.1E-03	1.3E-02	4.3E+01	3.1E+05	7.4E+04
	15 IN	LF	1.2E-02	1.8E+05	1.0E+04	5.5E+02	1.9E+02	3.1E-03	2.0E-02	6.4E+01	4.6E+05	1.1E+05
	18 IN	LF	1.6E-02	2.5E+05	1.4E+04	7.6E+02	2.7E+02	4.3E-03	2.7E-02	8.8E+01	6.4E+05	1.5E+05
	24 IN	LF	2.8E-02	4.3E+05	2.4E+04	1.3E+03	4.5E+02	7.2E-03	4.6E-02	1.5E+02	1.1E+06	2.6E+05
	30 IN	LF	4.2E-02	6.5E+05	3.7E+04	2.0E+03	6.9E+02	1.1E-02	7.0E-02	2.3E+02	1.7E+06	4.0E+05
	36 IN	LF	5.9E-02	9.2E+05	5.2E+04	2.8E+03	9.8E+02	1.6E-02	1.0E-01	3.2E+02	2.3E+06	5.6E+05
	42 IN	LF	8.0E-02	1.2E+06	7.0E+04	3.7E+03	1.3E+03	2.1E-02	1.3E-01	4.3E+02	3.1E+06	7.5E+05
	48 IN	LF	1.0E-01	1.6E+06	9.0E+04	4.8E+03	1.7E+03	2.7E-02	1.7E-01	5.6E+02	4.1E+06	9.7E+05
	60 IN	LF	1.6E-01	2.5E+06	1.4E+05	7.4E+03	2.6E+03	4.2E-02	2.7E-01	8.6E+02	6.2E+06	1.5E+06
Bioswale plug plants		EACH	1.0E-09	1.5E-02	2.0E-03	1.1E-04	2.0E-02	5.6E-10	1.5E-09	8.6E-06	1.5E-01	2.0E-02
High density polyethylene (HDPE) pipe	6 IN	LF	1.5E-07	6.0E+00	3.1E-01	2.5E-02	1.0E-02	2.2E-07	3.6E-07	2.4E-03	1.8E+01	2.6E+01
	8 IN	LF	3.0E-07	1.2E+01	6.2E-01	5.0E-02	2.1E-02	4.4E-07	7.2E-07	4.9E-03	3.6E+01	5.3E+01
Storm sewer catch basin		EACH	1.1E-01	1.8E+06	1.0E+05	5.4E+03	1.9E+03	3.2E-02	2.0E-01	6.3E+02	4.7E+06	1.1E+06
Manhole		EACH	8.6E-02	1.3E+06	7.5E+04	4.0E+03	1.4E+03	2.3E-02	1.4E-01	4.7E+02	3.4E+06	8.1E+05
Manhole cover		EACH	7.1E-03	1.1E+05	6.2E+03	3.3E+02	1.2E+02	1.9E-03	1.2E-02	3.8E+01	2.8E+05	6.7E+04
Mowing grass		MFS	1.1E-07	5.3E-01	3.2E-02	1.7E-03	3.4E-04	1.8E-10	7.8E-09	3.1E-03	6.6E-02	1.4E+00

Table 2 (continued): Unit Impacts of Construction and Maintenance Activities

Activity		Unit	Ozone Depletion (kg CFC-11 eq)	Climate Change (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogenics (CTUh)	Non-carcinogenics (CTUh)	Respiratory Effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil Fuel Depletion (MJ surplus)
Culvert headwall	15 IN	EACH	3.4E-02	5.3E+05	3.0E+04	1.6E+03	5.7E+02	9.0E-03	5.8E-02	1.9E+02	1.4E+06	3.2E+05
	18 IN	EACH	5.2E-02	8.1E+05	4.6E+04	2.4E+03	8.6E+02	1.4E-02	8.8E-02	2.8E+02	2.1E+06	4.9E+05
	24 IN	EACH	8.8E-02	1.4E+06	7.7E+04	4.1E+03	1.4E+03	2.3E-02	1.5E-01	4.8E+02	3.5E+06	8.3E+05
	30 IN	EACH	1.2E-01	1.9E+06	1.1E+05	5.8E+03	2.0E+03	3.3E-02	2.1E-01	6.7E+02	4.9E+06	1.2E+06
	36 IN	EACH	1.6E-01	2.5E+06	1.4E+05	7.5E+03	2.6E+03	4.2E-02	2.7E-01	8.6E+02	6.3E+06	1.5E+06
	42 IN	EACH	2.0E-01	3.0E+06	1.7E+05	9.1E+03	3.2E+03	5.1E-02	3.3E-01	1.1E+03	7.7E+06	1.8E+06
	48 IN	EACH	2.3E-01	3.6E+06	2.0E+05	1.1E+04	3.8E+03	6.1E-02	3.9E-01	1.2E+03	9.1E+06	2.2E+06
	60 IN	EACH	3.0E-01	4.7E+06	2.6E+05	1.4E+04	5.0E+03	7.9E-02	5.1E-01	1.6E+03	1.2E+07	2.9E+06
Backfilling with existing material		LCY	8.8E-07	4.1E+00	2.6E-01	1.3E-02	2.6E-03	1.4E-09	6.1E-08	2.6E-02	5.1E-01	1.1E+01
Landfilling		TON	2.8E-06	7.8E+00	1.5E+00	6.2E-02	1.5E-02	3.0E-07	1.3E-06	7.6E-03	3.9E+01	2.6E+01

3.2.3 Environmental Impacts of Drainage Components During Each Phase of Life

The impacts of each drainage component (basin, bioswale, culvert, grass swale, storm sewer, and pipe underdrain) can be divided into eight phases: construction materials, construction equipment, construction transportation, maintenance materials, maintenance equipment, maintenance transportation, operation and use, and end of life. The phase with the largest contribution to each impact category was determined for each of the six drainage components (Figure 9). The four drainage components above the horizontal line are affected by the operation and use phase, as water from the road directly enters these components. In the figure, the circle's color and symbol indicates the phase with the largest contribution to the corresponding impact category. The size of the circle is proportional to the percent contribution of that phase; therefore, the larger the circle size, the more dominant that phase is for the specified drainage component and impact category. The percent contributions and associated uncertainty for the dominant phase are summarized in Table 3 and the median contributions of all categories along with the contributions of specific materials are provided in Appendix E.

For both the culvert and underdrain, all 10 impact categories are dominated by construction materials. In both cases, this dominant material is precast concrete, which is used for the pipe and headwalls of the culvert and the headwalls for the outlets of the underdrain.

Of the drainage components affected by the operation and use phase (basin, bioswale, grass swale, and storm sewer), only grass swales and bioswales have impact categories that are dominated by this phase. For grass swales, the impact categories dominated by operation and use are eutrophication, carcinogenics, noncarcinogenics, and ecotoxicity. Grass seed is the only material included within a grass swale; therefore, construction materials is not the largest contributing phase for any of the impact categories. For ozone depletion, climate change, acidification, respiratory effects, and fossil fuel depletion, the largest contributing phase is maintenance equipment due to the mowing of grass swales, which occurs three times a year.

Bioswales are also dominated by the operation and use phase for eutrophication, noncarcinogenics, and ecotoxicity. As with the grass swales, the maintenance equipment is the largest contributor to ozone depletion and respiratory effects but the additional construction materials required for bioswales as compared with grass swales (e.g., sand, topsoil) makes construction materials the largest contributor to the impact categories of climate change, smog, acidification, carcinogenics, and fossil fuel depletion. For both grass swales and bioswales, there is uncertainty surrounding the results (Table 3) mainly due to the uncertainty surrounding the pollutant treatment efficiencies of grass swales and bioswales. Because of this uncertainty, the largest contributing phase could vary, especially for the impact categories for which the percent contribution of the largest contributing phase is relatively small.

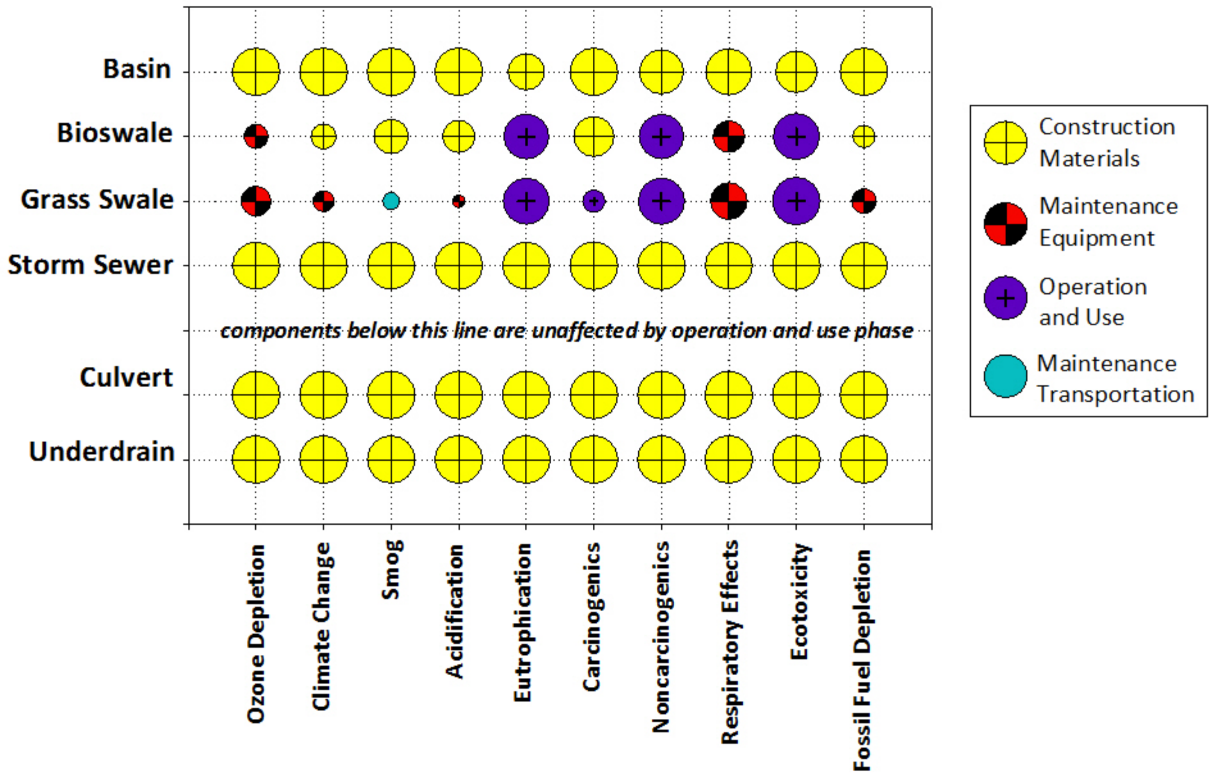


Figure 9: Largest Life Cycle Phase Contributions to Environmental Impacts of Each Drainage Component

Both basins and storm sewers are strongly dominated by construction materials for every impact category. In both cases, this dominance is the result of the precast concrete used for the reinforced concrete pipe. Unlike bioswales, grass swales, and basins, storm sewers achieve no pollutant removal; therefore, the environmental impacts from the operation and use phase are larger for a storm sewer than they are for the other drainage components. Despite this lack of removal, the effects of the operation and use phase are not noticeable as compared to the impacts of the concrete used as a construction material. The four drainage components that include concrete (basin, storm sewer, culvert, underdrain) are dominated by construction materials for all 10 impact categories, further highlighting the dominant effect of concrete within all categories of the LCA.

Table 3: Largest Life Cycle Phase Contributions to Environmental Impacts of Each Drainage Component

Largest Contributing Phase
Median (10th percentile, 90th percentile) (%)

Impact Category	Basin	Bioswale	Grass Swale	Storm Sewer	Culvert	Pipe Underdrain
Ozone Depletion	*Con. Mat.* 99.4 (99.4, 99.4)	*Main. Equip.* 50.6 (50.4, 50.9)	*Main. Equip.* 62.8 (62.1, 63.8)	*Con. Mat.* 98.7 (97.9, 99.1)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.7 (99.7, 99.7)
Climate Change	*Con. Mat.* 99.8 (99.8, 99.8)	*Con. Mat.* 53.1 (50.8, 55.4)	*Main. Equip.* 44.0 (40.2, 48.1)	*Con. Mat.* 99.5 (99.2, 99.7)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.9 (99.9, 99.9)
Smog	*Con. Mat.* 99.8 (99.7, 99.8)	*Con. Mat.* 71.7 (67.0, 76.6)	*Main. Trans.* 35.7 (23.3, 45.7)	*Con. Mat.* 98.4 (97.5, 98.9)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.6 (99.6, 99.6)
Acidification	*Con. Mat.* 99.8 (99.8, 99.8)	*Con. Mat.* 67.6 (63.8, 71.5)	*Main. Equip.* 28.0 (25.4, 31.0)	*Con. Mat.* 99.0 (98.3, 99.3)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.7 (99.7, 99.8)
Eutrophication	*Con. Mat.* 76.6 (59.1, 88.5)	*Use* 93.6 (86.8, 97.0)	*Use* 97.0 (93.3, 98.8)	*Con. Mat.* 98.9 (97.9, 99.3)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.9 (99.9, 99.9)
Carcinogenics	*Con. Mat.* 100.0 (74.5, 100.0)	*Con. Mat.* 83.7 (1.5, 91.4)	*Use* 47.2 (0.0, 99.8)	*Con. Mat.* 100.0 (99.4, 100.0)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 100.0 (100.0, 100.0)
Non-carcinogenics	*Con. Mat.* 92.3 (65.1, 100.0)	*Use* 93.1 (0.8, 99.0)	*Use* 96.9 (3.5, 99.5)	*Con. Mat.* 99.8 (99.0, 99.9)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 100.0 (100.0, 100.0)
Respiratory Effects	*Con. Mat.* 97.1 (97.1, 97.1)	*Main. Equip.* 66.3 (66.0, 66.7)	*Main. Equip.* 77.2 (76.3, 78.6)	*Con. Mat.* 98.7 (98.0, 99.0)	*Con. Mat.* 99.9 (99.9, 99.9)	*Con. Mat.* 99.8 (99.8, 99.8)
Ecotoxicity	*Con. Mat.* 86.6 (54.9, 99.9)	*Use* 96.5 (8.3, 99.2)	*Use* 99.5 (56.3, 99.9)	*Con. Mat.* 99.7 (98.7, 100.0)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 100.0 (100.0, 100.0)
Fossil Fuel Depletion	*Con. Mat.* 99.2 (99.2, 99.2)	*Con. Mat.* 47.2 (45.3, 49.1)	*Main. Equip.* 52.6 (48.0, 57.3)	*Con. Mat.* 98.3 (97.3, 98.9)	*Con. Mat.* 100.0 (100.0, 100.0)	*Con. Mat.* 99.6 (99.6, 99.6)

3.2.4 The Environmental and Economic Implications of Individual Design Decisions

Within each of the six drainage components, specific decisions can impact the LCA and LCC results of the drainage system. For each of the six components, the effect of each design decision on climate change, eutrophication, and total cost was evaluated by adjusting each design decision individually. If the design decision was a discrete choice (e.g., including an erosion blanket) then the effect of switching that discrete choice was evaluated. If the design decision was a continuous choice (e.g, length of pipe) then that parameter was increased by 25%. The ratio of the increase in impact (climate change, eutrophication, and cost) was compared to making a discrete decision or to a 25% increase in a continuous decision (Figure 10).

For basins (Figure 10A), increasing the area of the basin had the largest impact on total cost, as this required additional excavation. Both an increase in outlet pipe diameter and length resulted in increases in climate change and eutrophication due to an increase in the amount of concrete required, but this change had little effect on cost since cost is dominated by excavation. Using a detention basin (which only holds water during a storm event) instead of a retention basin (which holds water at all times) increases eutrophication as retention basins provide better pollutant removal than detention basins. Including an erosion blanket had little effect on climate change, eutrophication, or cost of a basin.

For bioswales (Figure 10B), increasing the length had the largest effect on climate change, eutrophication, and cost as an increase in length requires additional materials, equipment, and transportation for both construction and maintenance. An increase in the top width of the swale increased both total cost and climate change as this increases the surface area of the swale, which requires additional plug plants, topsoil, fertilizer, and herbicide. An increase in bottom width when the top width and side slope are held constant decreases the amount of surface area; however, because there is a sand layer below the flat part of the bioswale, an increase in bottom width increases the amount of required sand which therefore increases the total cost and climate change. An increase in top width or bottom width has little effect on eutrophication as eutrophication impacts are dominated by the operation and use phase. In reality, changes in the width of swale affects infiltration, which would affect eutrophication impacts; however, TRACI does not distinguish between emissions to surface water and emissions to groundwater and, as a result, the impacts of decreasing infiltration and increasing discharge to surface waters would not be observed in calculated impacts.

For culverts (Figure 10C), both increasing the diameter and length had a large effect on climate change, eutrophication, and total cost as both of these decisions increased the amount of concrete required for the culvert. Although adding a headwall increases the amount of concrete required for the culvert, this decision had the smallest effect on the three categories because the amount of concrete required for the culvert pipe is significantly greater than the amount of concrete required for a headwall.

For grass swales (Figure 10D), an increase in length had the greatest effect on climate change, eutrophication, and total cost for the same reasons that this is true for bioswales. As with a bioswale, an increase in top width increases the surface area of the grass swale, which increases impacts. An increase in bottom width when top width and side slope are held constant decreases the amount of surface area of the swale, which decreases the amount of seed, fertilizer, and herbicide required. Since there is no sand layer below the surface like there is for a bioswale, the increase in bottom width provides a decrease in impacts. Inclusion of an erosion blanket played a more significant role in grass swale impacts than it did for bioswale impacts since bioswales required other materials (e.g., sand, topsoil), which lessened the relative effects of the addition of a bioswale erosion blanket.

For storm sewers (Figure 10E), increasing diameter and length increased climate change, eutrophication, and total cost due to the increase in the amount of concrete required. Including a curb and gutter increased all three categories as well, but not as significantly since the reinforced concrete pipe dominates the impacts of all three categories. Using sand as a backfill material as opposed to backfilling with existing material increased the total cost of the storm sewer; however, it had minimal effects on climate change or eutrophication as these impact categories are strongly dominated by the required concrete.

For pipe underdrains (Figure 10F), an increase in diameter had the largest effect on total cost due to the increased amount of HDPE needed for the pipe material. However, an increase in diameter had little effect on climate change or eutrophication because the precast concrete used for the headwalls for the underdrain outlets dominates these impact categories and an increase in diameter does not affect the number of headwalls required. Increasing the length of the pipe underdrain impacted all three categories, as an increase in length requires additional HDPE for the pipe material as well as an increase in the number of outlet structures and therefore precast concrete for the headwalls. As with storm sewers, using sand as a backfill material for the underdrain increased the total cost but did not affect climate change or eutrophication because precast concrete dominates these impacts.

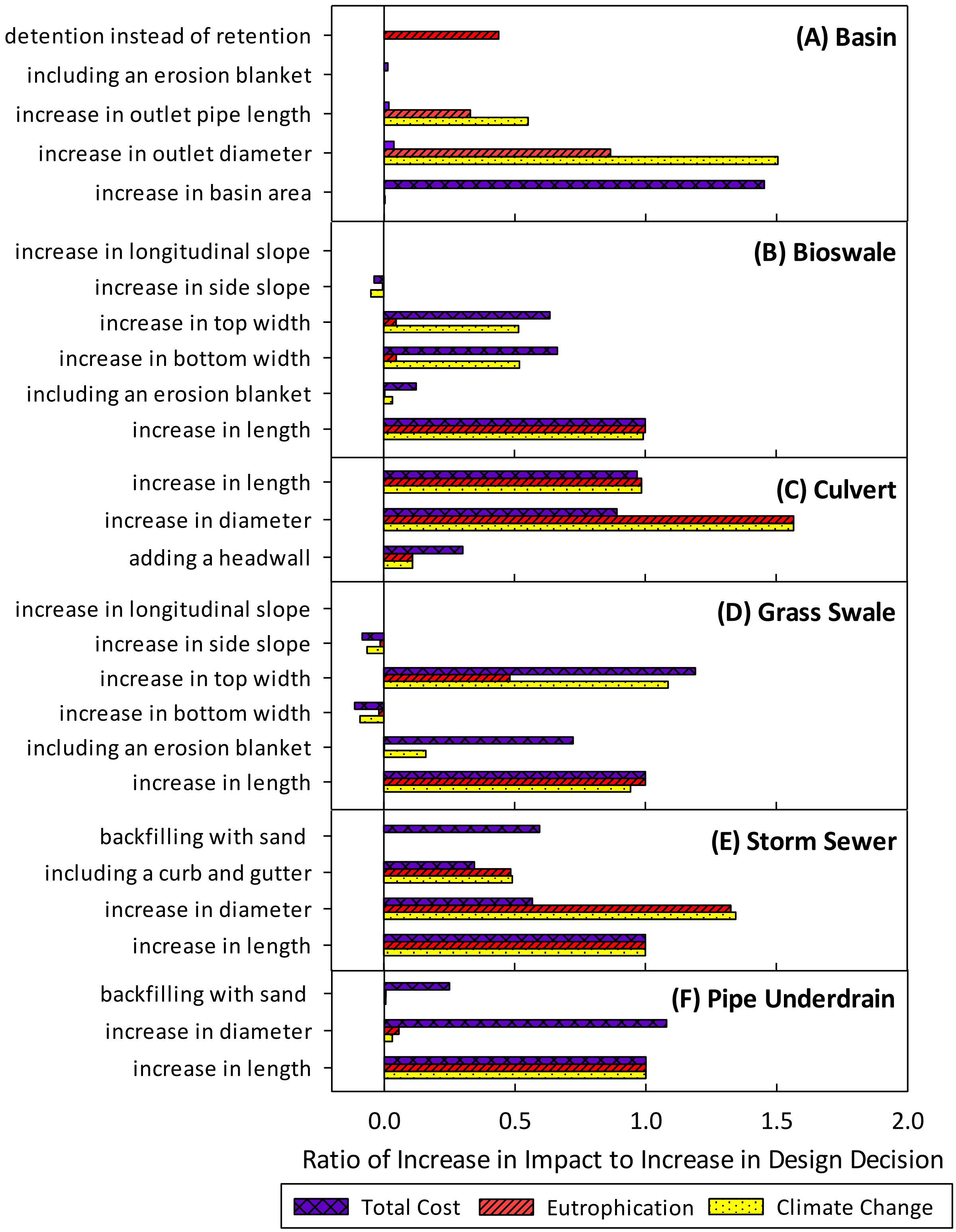


Figure 10: Effect of Design Decisions on Environmental and Economic Impacts

In addition to these specific design decisions, environmental impacts are also sensitive to the flow rate through the drainage system. An increase in flow requires construction and maintenance of a larger drainage system, resulting in greater environmental impacts. Grass swales, bioswales, and storm sewers were sized for a variety of flow rates and the associated climate change impacts were compared (Figure 11). The sizes of grass swales and bioswales are continuous decisions; therefore, the climate change impacts for these two components are continuous and increase with flow rate as the required swale sizes increase. Storm sewer sizes are discrete decisions as pipe diameters must be chosen based on standard pipe sizes. Therefore, the climate change impacts for storm sewers is a stepwise function of flow with each step representing a necessary upgrade of pipe size to accommodate the additional flow. Grass swale and bioswale climate change impacts are similar with bioswales having slightly greater impacts due to their additional required materials (e.g., sand and topsoil). Storm sewer climate change impacts are significantly greater than both the grass swales and bioswales as they are dominated by the use of concrete.

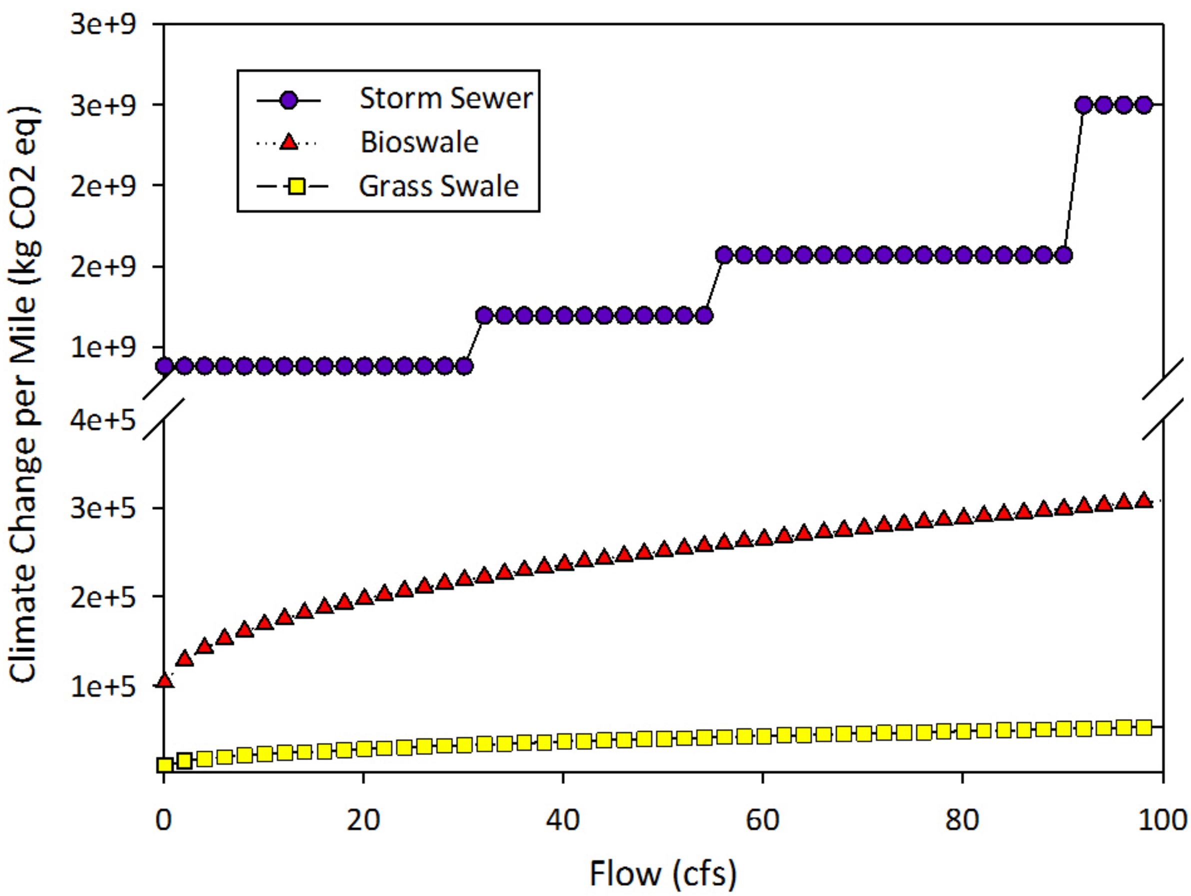


Figure 11: Sensitivity of Climate Change Impacts to Flow

3.2.5 Local vs. Global Environmental Trade-offs for Roadway Drainage

Bioswales, a stormwater green infrastructure technique, are becoming more prevalent as replacements for grass swales as they provide filtration of pollutants and promote additional infiltration. These two roadway drainage techniques were compared to each other and to storm sewers for each of the ten impact categories. The impacts per mile for bioswales and storm sewers were calculated relative to grass swales with results are broken down into life cycle phases (Figure 12). The operation and use phase (fate and transport pollutants) comparably dominates the impact categories of eutrophication, noncarcinogenics, and ecotoxicity for both grass swales and bioswales. However, the bioswales have more than 4 times the impacts than grass swales for the categories of ozone depletion, climate change, smog, acidification, carcinogenics, respiratory effects, and fossil fuel depletion. This is due to the additional construction and maintenance required for bioswales.

The use of the LCA and LCC results for decision-making would suggest that grass swales might be a better choice than bioswales because of the large global environmental impacts of bioswales relative to grass swales. However, comparing all 3 conveyance elements shows that storm sewers have impacts that are orders of magnitude greater than the impacts of grass swales and bioswales; therefore, the effects of the additional bioswale materials (e.g., sand, topsoil) become insignificant. Previous studies have also shown the significant impact concrete has on LCA results for stormwater green infrastructure (De Sousa et al., 2012; O'Sullivan et al., 2015; Spatari et al., 2011; Wang et al., 2013). These dominant effects of concrete suggest that when comparing technologies without concrete materials (e.g., bioswales and grass swales), LCA may not be a good decision-making tool. The focus should instead shift to local water quantity and water quality impacts. Choosing one green infrastructure technique over another may increase or decrease global impacts; however, they have the potential to show great improvements for the local environment. Therefore, local environmental benefits should be the center of decision-making rather than global environmental impacts when comparing grass swales and bioswales.

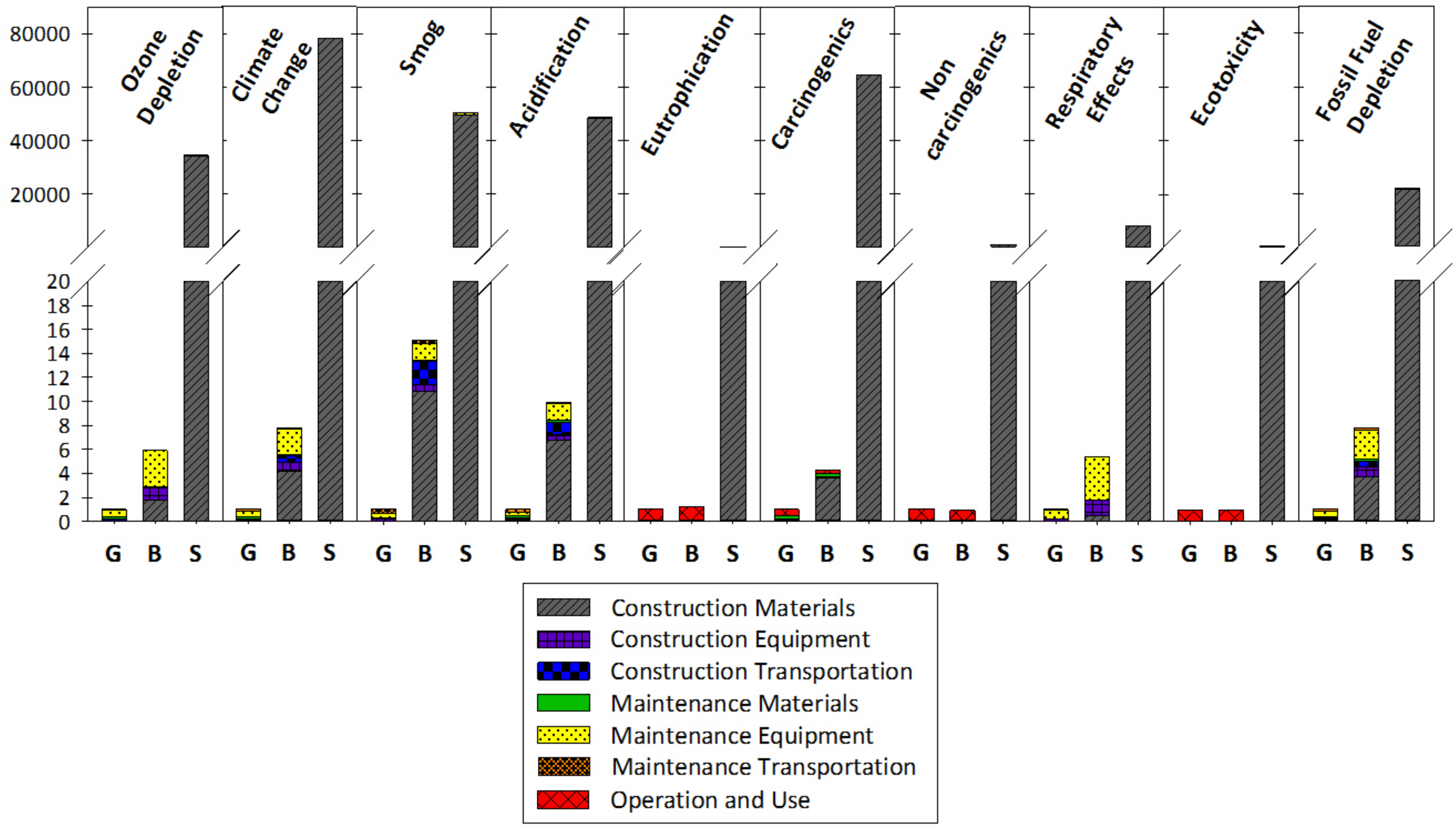


Figure 12: Comparison of Grass Swales (G), Bioswales (B), and Storm Sewers (S)

CHAPTER 4: CONCLUSIONS

When evaluating elements of roadway drainage projects, drainage components (basins, bioswales, culverts, grass swales, storm sewers, pipe underdrains) that used concrete as a construction material consistently had larger climate change impacts than the components which did not use any concrete. The components that used concrete included culverts (in headwalls and reinforced concrete pipe), storm sewers (in reinforced concrete pipe, curb and gutter, catch basins, and manholes), basins (in headwalls and reinforced concrete pipe of the outlet structure), and pipe underdrains (in headwalls of the outlet structures). Therefore, the amount of concrete used for these structures should be limited as much as possible. Additionally, alternative materials to concrete or alternative concrete mix designs with lesser environmental consequences could provide a reduction in global environmental impacts for these drainage components.

While concrete consistently dominates climate change impacts across an entire drainage system, it does not consistently govern the total cost of the system. Depending upon the sample project considered, certain construction and maintenance activities were shown to have larger contributions to total cost than concrete (e.g., excavation) even though these activities did not have large relative contributions to climate change. Similarly, certain activities were shown to have larger contributions than concrete to a project's total mass of materials (e.g., sand) but with very small contributions to climate change. Because of this, neither cost nor mass provide a valid cut-off criterion; however, simply accounting for the concrete in the drainage system can account for the vast majority of climate change impacts.

Within each drainage component, the phase that most frequently resulted in the largest environmental impacts was construction materials. This phase dominated all impact categories for each of the components that used concrete (basins, storm sewers, culverts, underdrains). For grass swales and bioswales, the operation and use phase (local water quality impacts) dominated the categories of eutrophication, noncarcinogenics, and ecotoxicity while the remaining impact categories were either affected by construction materials, maintenance equipment, or maintenance transportation. This shows that local water quality does play a role in the total life cycle impacts of a roadway drainage system; however, these impacts are only noticeable relative to other phases for grass swales and bioswales, which do not require concrete as a construction material.

Among the three major conveyance options considered, grass swales and bioswales had significantly smaller climate change impacts than storm sewers. Additionally, storm sewers had larger impacts on local water quality (operation and use phase) than grass swales and bioswales since storm sewers do not achieve any pollutant removal. While the operation and use phase impacts for storm sewers are larger in magnitude than the operation and use phase impacts for grass swales or bioswales, these impacts are not noticeable relative to the impacts of the concrete used for storm sewers. When comparing storm sewers to grass swales or bioswales, storm sewers have larger global environmental impacts, local environmental impacts, and cost. Therefore, the use of storm sewers should be limited as much as possible. In cases when this is not possible (e.g., in an urban area when space is not available for swales), drainage designers should aim to minimize the amount of concrete. Additionally, designers could consider alternative materials to concrete or alternative materials within the concrete itself, for example replacements for Portland cement (Gartner, 2004).

While the impacts of storms sewers (local environmental, global environmental, and cost) are significantly larger than grass swales and bioswales, distinguishing between the impacts of grass swales and bioswales is more complicated. In impact categories that are not affected by the operation and use phase (ozone depletion, climate change, smog, acidification, respiratory effects, and fossil fuel depletion), the bioswales had larger impacts than the grass swales. This was because while grass swales are simply excavated, grass-lined channels, bioswales have layers of sand and prepared topsoil and use plug plants on the channel's surface. The additional materials, equipment, and maintenance required for bioswales result in larger impacts for these impact categories not affected by the operation and use phase. However, bioswales are designed to achieve more pollutant removal than traditional grass swales, which has the potential to improve the impact categories of eutrophication, ecotoxicity, carcinogenics, and noncarcinogenics. The large amount of uncertainty surrounding the pollutant removal efficiencies of grass swales and bioswales makes it impossible to definitively say whether or not bioswales or grass swales perform better in these categories during the operation and use phase. Moreover, bioswales can be designed in a variety of ways; therefore, it is possible that certain designs could have the potential to reduce both global environmental impacts (by limiting material impacts) and local environmental impacts (by achieving better pollutant removal).

The differences in environmental impacts between grass swales and bioswales become insignificant when considering these two conveyance options alongside storm sewers. For example, the climate change impacts of bioswales were found to be about 8 times greater than that of grass swales; however, climate change impacts of storm sewers were found to be over 70,000 times greater than that of grass swales. Considering these global impacts when deciding between a storm sewer system and a swale system is important and can help guide decision-making, but considering global impacts when comparing grass swales and bioswales may not be a relevant discussion. When considering grass swales or bioswales, the focus of design should instead be about the local environmental impacts. If bioswales can improve local water quantity and water quality impacts, then the additional global environmental impacts that result from the use of additional materials may be worth the trade-off. Therefore, future research and design should aim to study different types of bioswale designs and their treatment efficiency of pollutants in order to improve their effectiveness.

CHAPTER 5: ENGINEERING SIGNIFICANCE

Conventional roadway drainage systems are designed to cost-effectively manage runoff and keep the roadway safe for travel. However, the ability of drainage technologies to remove pollutants (e.g., sediment, nutrients, metals) is now becoming a consideration for roadway drainage design due to the impacts that roadway runoff can have on local water quality. While these local environmental impacts have been considered in the past, the global environmental impacts associated with the construction and maintenance of roadway drainage systems has not previously been a part of evaluating drainage system design. In order to collectively evaluate the environmental (both local and global) and economic impacts of roadway drainage systems, this research connected design decisions to fate and transport modeling, LCA, and LCC.

This research showed which drainage components (basins, bioswales, culverts, grass swales, storm sewers, pipe underdrains) have the largest contributions to environmental and economic impacts when considering a roadway drainage system as a whole. When designers have the flexibility to choose which drainage components are utilized, this knowledge can be used to choose the options that limit the associated environmental and economic impacts. Additionally, this research showed for each drainage component which particular life cycle phases (e.g., construction materials, operation and use) and design decisions (e.g., pipe diameter, inclusion of erosion blanket) have the largest effects on total impacts. Once the decision about which drainage component to be used is made, this information can help improve the design within that specific component.

Designers of roadway drainage systems can use the provided environmental impacts per unit of applicable construction and maintenance activities in order to estimate the environmental impacts associated with various designs of drainage systems. In a similar way that designers assemble cost bids for the design of a drainage system, they could also come up with environmental bids using these unit impacts. This way, contractors could submit both environmental and economic bids for drainage system design and government agencies could choose contractors using environmental metrics in addition to existing economic metrics during the decision-making process.

Additionally, this research discusses the trade-offs between global and local environmental impacts and when knowledge of each could be useful for roadway drainage system design. LCA has frequently been used to evaluate wastewater and drinking water technologies in the past, and its application to stormwater technologies is becoming more prevalent, especially for evaluating the sustainability of green infrastructure techniques. As LCA becomes more widely used as a stormwater evaluation tool, it is important to understand when it is applicable and when a different evaluation metric (e.g., local water quality) should be the main focus. The significant differences in impacts between storm sewers and swales (either grass swales or bioswales) advocate the need for consideration of global impacts when choosing between these two systems. However, the smaller differences between impacts of grass swales and bioswales suggest that global impacts may not be a good metric for decision-making. These results can prompt both designers and researchers to holistically think about the spatial variation of environmental impacts and when LCA may or may not a relevant evaluation tool.

Finally, this work can fit within a larger LCA framework for roadway systems that considers other aspects of roadway design such as pavement and bridges. Since the highway network in the United States and abroad is extensive and the construction and maintenance of the highways is a major industry, reducing the environmental impacts of these systems could have significant impacts at a large scale and ultimately promote the importance of environmental impacts within the decision-making process for roadway construction and maintenance.

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Appendix A – Assumed Cross Sections

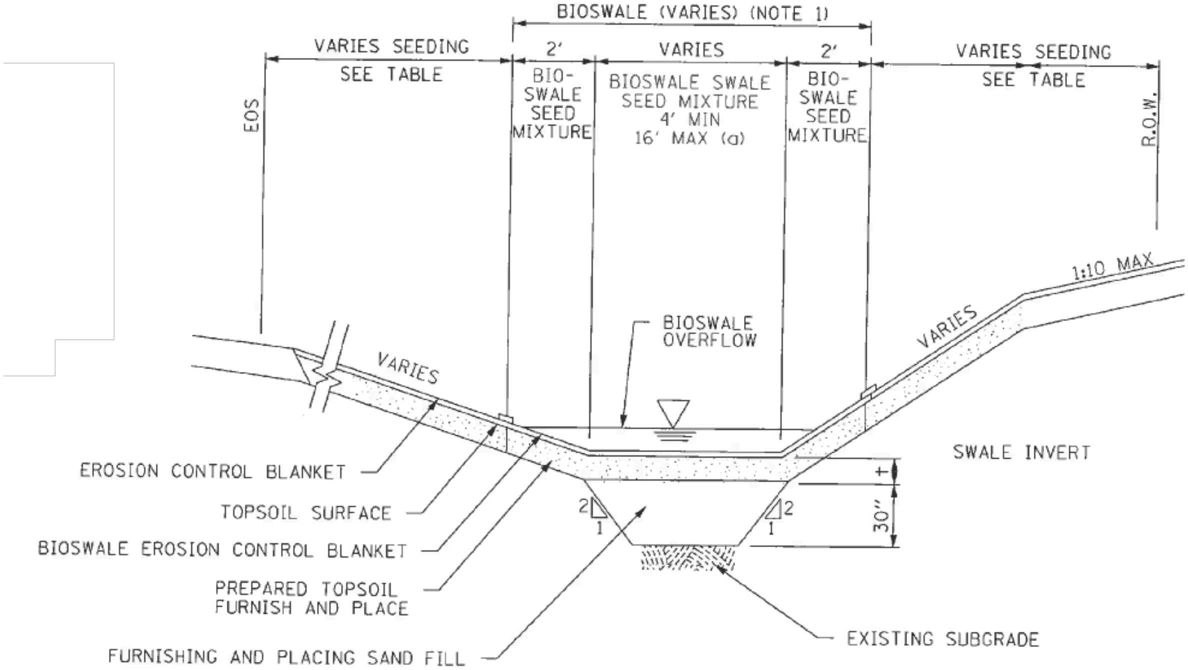


Figure A1: Assumed Bioswale Cross Section (provided by the Illinois Tollway)

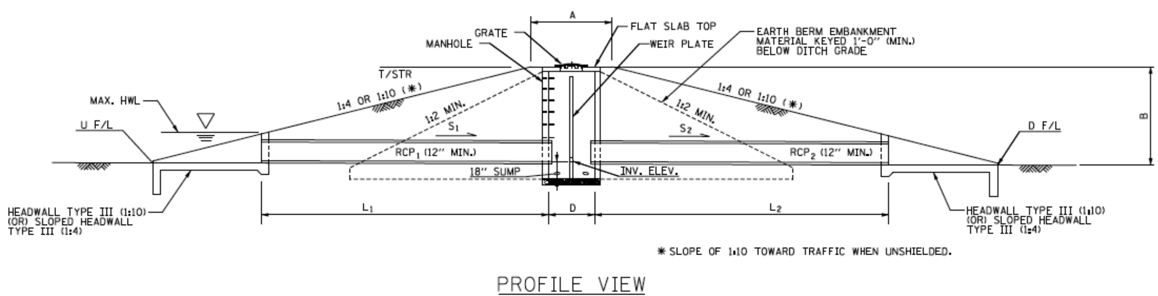


Figure A2: Assumed Basin Outlet Structure (provided by the Illinois Tollway)

Appendix B – NONROADS Equipment Emissions Calculations

The USEI process *Diesel, burned in building machine/GLO US-EI U* was modified using the EPA's NONROADS model to obtain equipment-specific impacts. The following emissions from the USEI process were substituted with emissions from NONROADS.

> **Substituted Emissions:** Carbon dioxide, fossil; Carbon monoxide, fossil; Methane, fossil; Nitrogen oxides; Non-methane volatile organic compounds (NMVOC); Particulates <2.5 µm; Particulates, > 2.5 µm, <10 µm; Sulfur dioxide

NONROADS emissions were converted to emissions that were included within TRACI using EPA conversion factors (US EPA, 2010a, 2010b). These factors are summarized in the table below. The following figure shows how the impacts for the NONROADS emissions (blue) compared to the impacts for the original USEI emissions (yellow) for each equipment type. The USEI process *Diesel, at regional storage/US- US-EI U* was used to account for the diesel itself.

Table B1: Conversion Factors for NONROADS Emissions

NONROADS Emission	Conversion Factor	TRACI Emission
Total hydrocarbons (THC) - exhaust	0.016	Methane
	0.984 * 1.053	Non-methane volatile organic compounds (NMVOC)
Total hydrocarbons (THC) - crankcase	1.053	Non-methane volatile organic compounds (NMVOC)
Carbon monoxide (CO)	1	Carbon monoxide
Nitrogen oxides (NO_x)	1	Nitrogen oxides
Carbon dioxide (CO_2)	1	Carbon dioxide
Sulfur dioxide (SO_2)	1	Sulfur dioxide
Particulate matter (PM) - exhaust	0.97	Particulates < 2.5 µm
	0.03	Particulates > 2.5 µm, < 10 µm

Appendix C – Probability Distributions for Uncertainty Analysis

Rational Method Coefficient for Road
Triangular distribution
- Minimum = 0.7
- Probable = 0.9
- Maximum = 1.0

Transportation Distance
Triangular distribution
- Minimum = 2 miles
- Probable = 10 miles
- Maximum = 20 miles

Interest Rate
Triangular distribution
- Minimum = 3%
- Probable = 6%
- Maximum = 8%

Total Cost of Construction and Maintenance Activities
Triangular distribution
- Minimum = -10% of RS Means cost
- Probable = RS Means cost
- Maximum = +10% of RS Means cost

Frequency of Maintenance Activities
Seeding, fertilizing, grading/compacting (these activities vary collectively)
Triangular distribution
- Minimum = 10 years
- Probable = 15 years
- Maximum = 20 years

Pipe cleaning (this activity varies separately from the others)
Triangular distribution
- Minimum = 10 years
- Probable = 15 years
- Maximum = 20 years

Herbicide, mowing (these activities are not varied)

Weight of Equipment
Triangular distribution
- Minimum = -10% of manufacture estimate
- Probable = manufacture estimate
- Maximum = +10% of manufacture estimate

Initial Concentrations of Pollutants in Runoff

Empirical distribution

- Raw data from the National Stormwater Quality Database (NSQD) for land use classification of 100% highways and/or freeways.
- Histograms of concentrations for each of the 14 pollutants considered are shown in Figure C1.

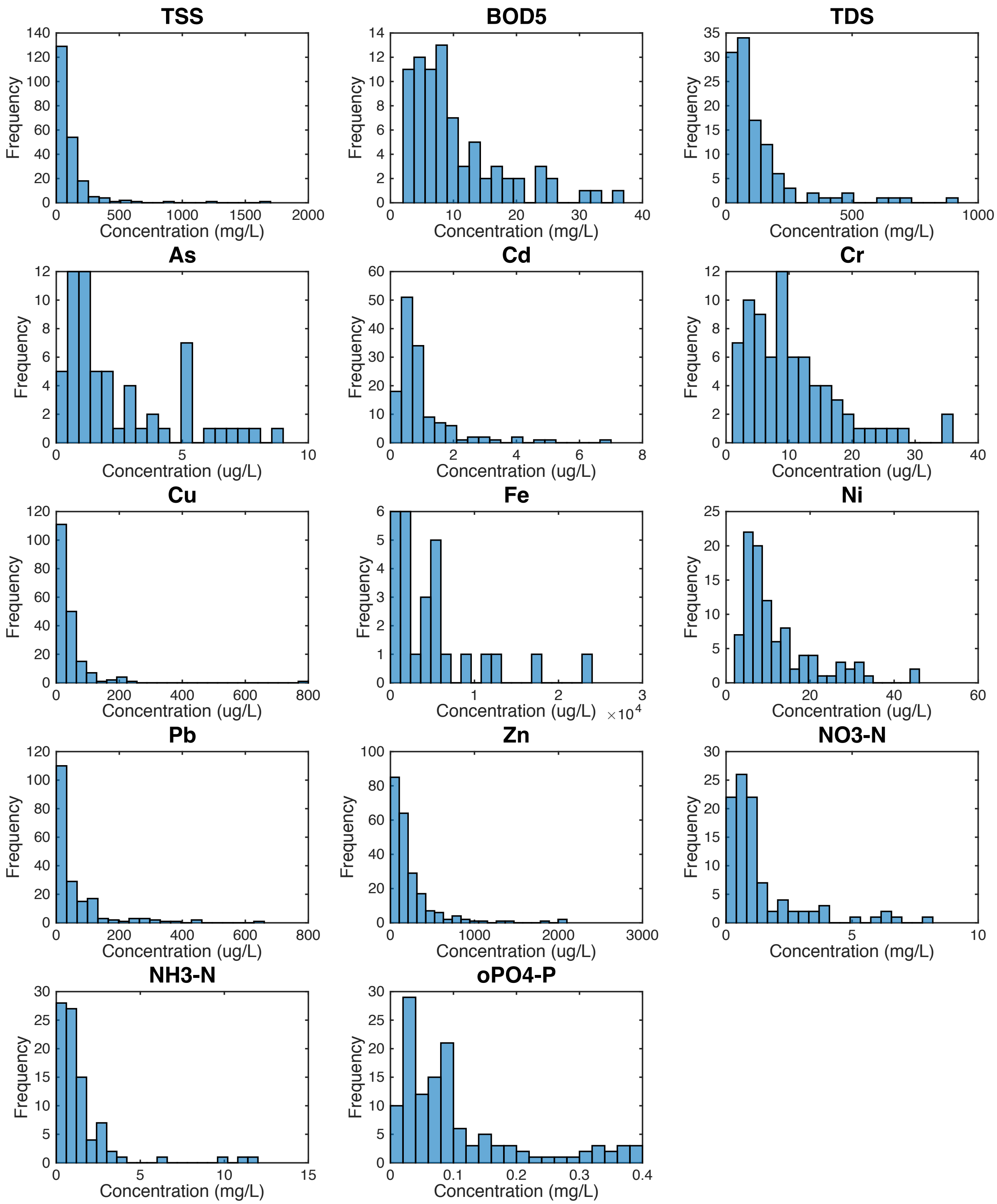


Figure C1: Histograms for NSQD Concentrations used for Uncertainty Analysis

Removal Efficiency for Grass Swales, Bioswales, and Basins (wet and dry)

Triangular distribution

- Minimum = minimum value (negative values replaced by zero)
- Probable = average of endpoint values for the section of the cumulative distribution plot that had the steepest slope (excluding the first section); in cases where the slopes did not significantly vary from each other (less than 30% variation), a uniform distribution was used instead of a triangular distribution (probable value not applicable)
- Maximum = maximum value

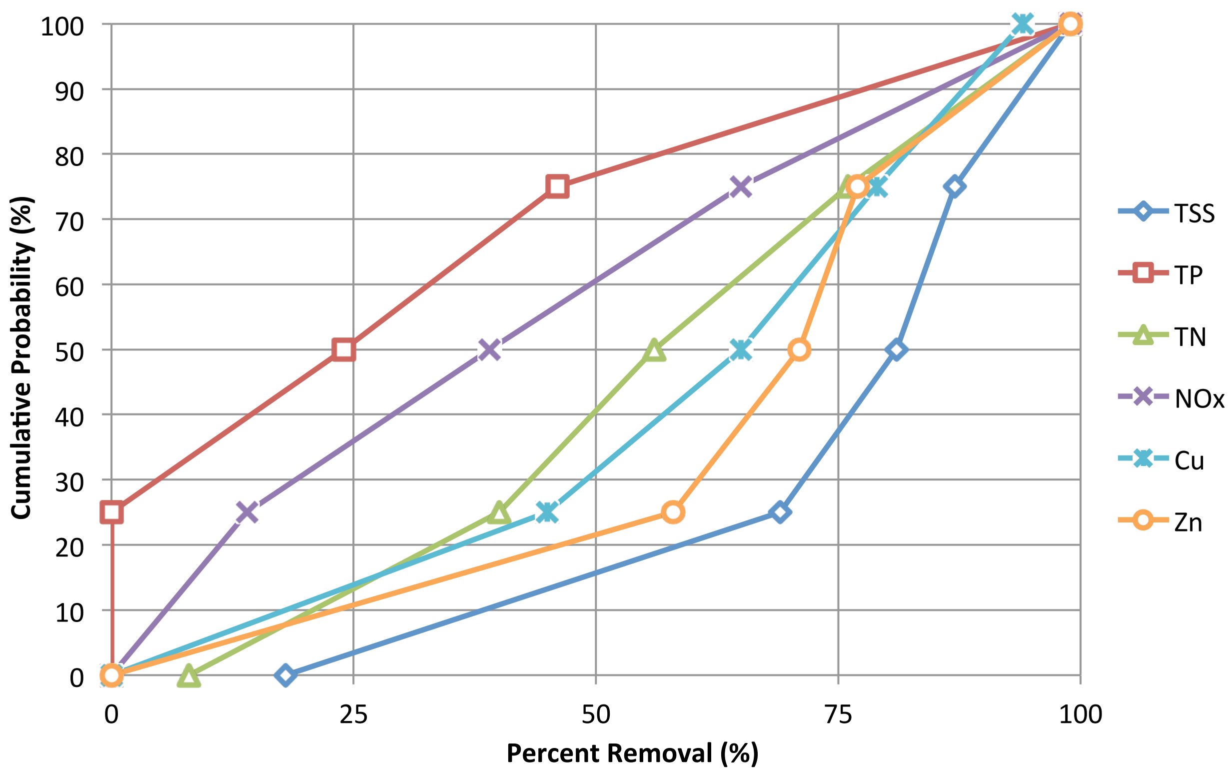


Figure C2: Cumulative Probability for Removal Efficiency of Grass Swales (Open Channels)

Table C1: Distributions for Grass Swale Removal Efficiencies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	*Triangular*	*Triangular*	*Triangular*	*Triangular*	*Triangular*	*Triangular*
Min	18	0	8	0	0	0
Probable	84	35	48	26.5	72	74
Max	99	99	99	99	94	99

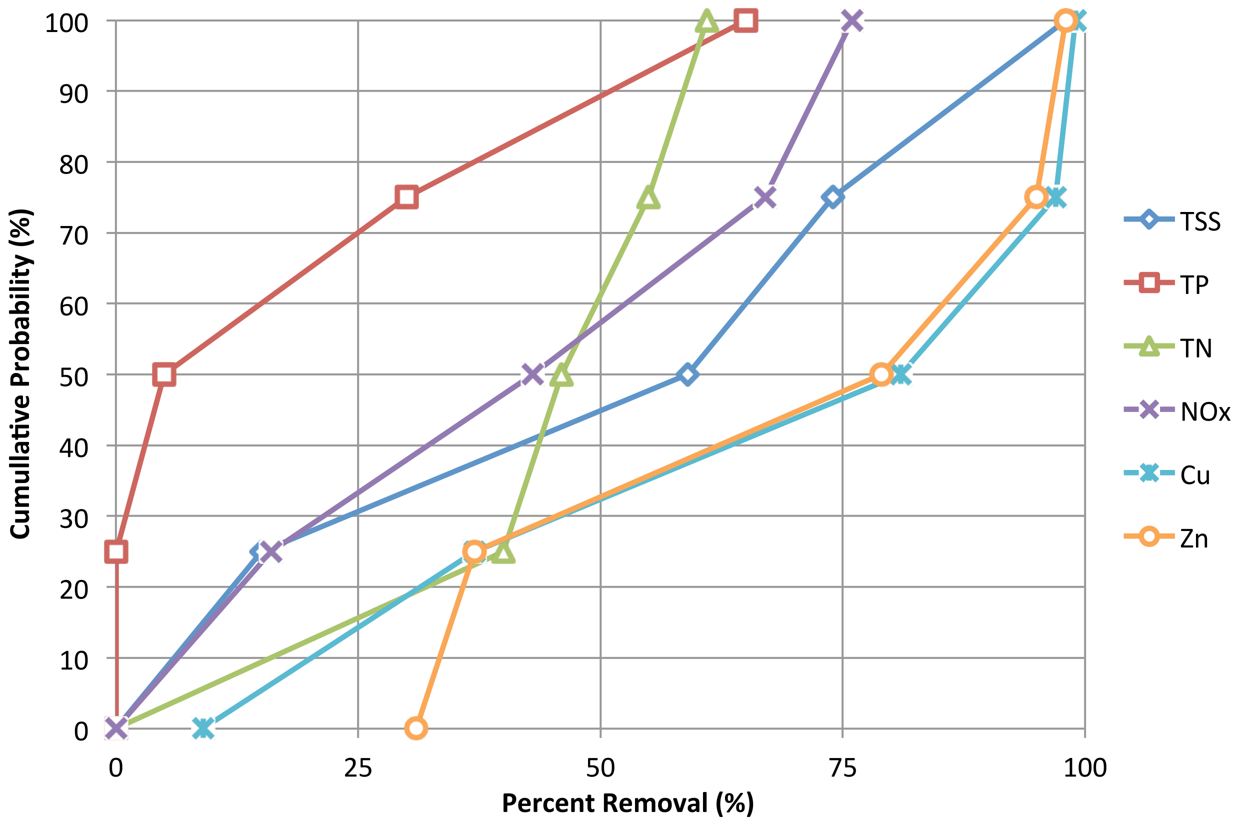


Figure C3: Cumulative Probability for Removal Efficiency of Bioswales (Bioretention)

Table C2: Distributions for Bioswale Removal Efficiencies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	*Triangular*	*Triangular*	*Triangular*	*Triangular*	*Triangular*	*Triangular*
Min	59	5	46	43	81	79
Probable	0	0	0	0	9	31
Max	66.5	17.5	46	71.5	98	96.5

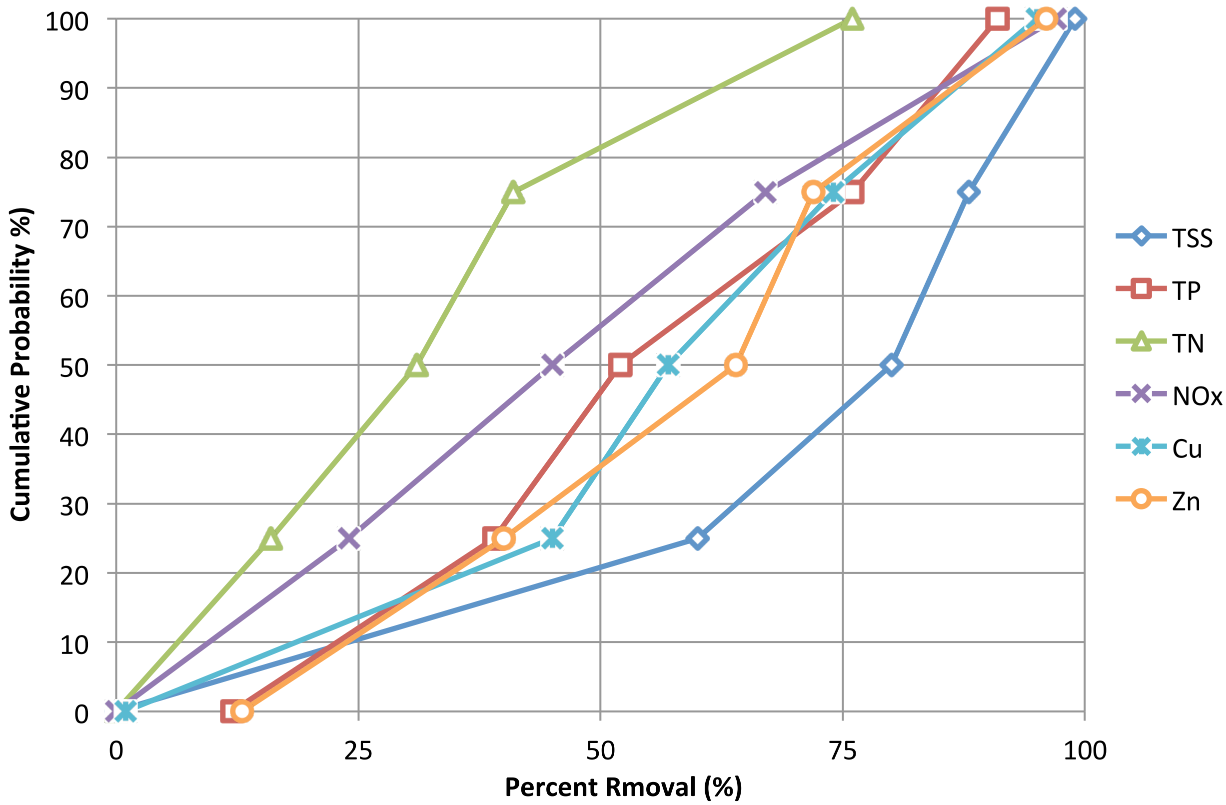


Figure C4: Cumulative Probability for Removal Efficiency of Retention/Wet Basins (Wet Basin)

Table C3: Distributions for Retention/Wet Basin Removal Efficiencies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	*Triangular*	*Triangular*	*Triangular*	*Uniform*	*Triangular*	*Triangular*
Min	0	12	0	0	1	13
Probable	84	45.5	36	N/A	51	68
Max	99	91	76	97	95	96

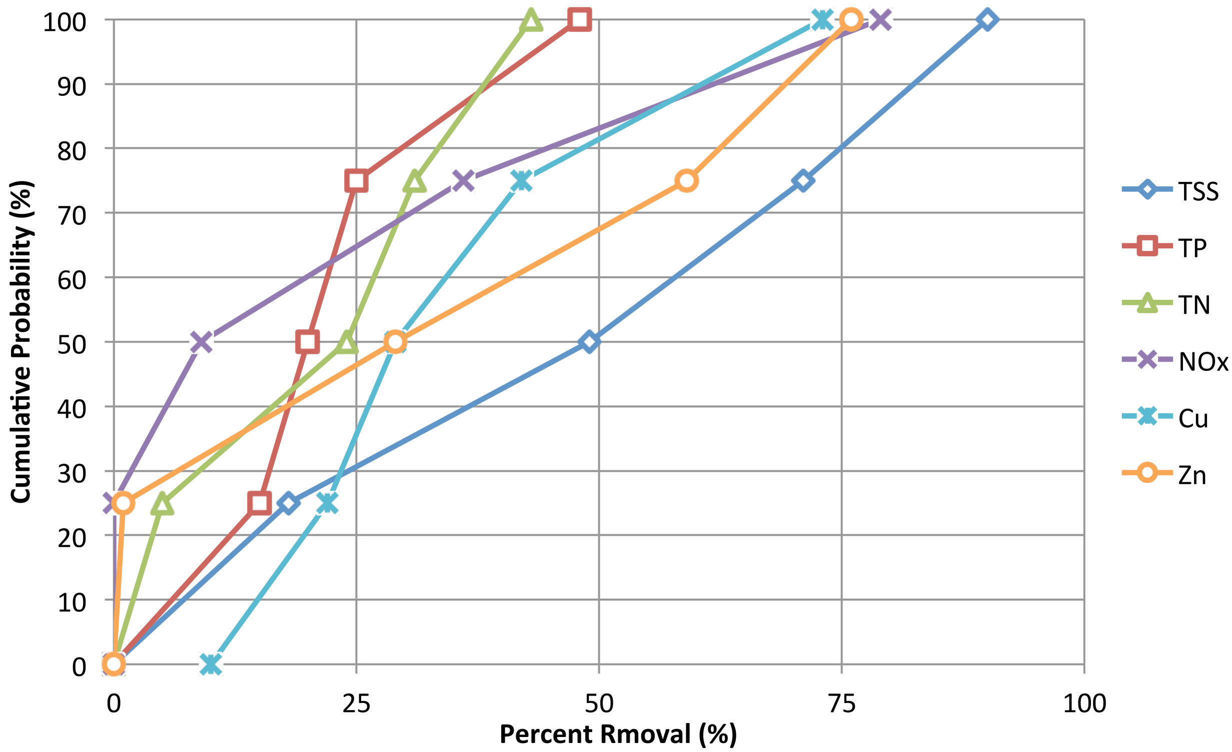


Figure C5: Cumulative Probability for Removal Efficiency of Detention/Dry Basins (Dry Basin)

Table C4: Distributions for Detention/Dry Basin Removal Efficiencies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	*Uniform*	*Triangular*	*Triangular*	*Triangular*	*Triangular*	*Triangular*
Min	0	0	0	0	10	0
Probable	N/A	20	27.5	4.5	25.5	67.5
Max	90	48	43	79	73	76

Appendix D – Productivity and Costs of Construction and Maintenance Activities

Table D1: General Activities Productivity and Cost (RS Means)

Construction/Maintenance Activity	RS Means Activity Name	Unit	Productivity (hours/unit)	Material ($)	Labor ($)	Equipment ($)	Total with O&P ($)
Sewer trench excavation	4' to 6' deep, 3/4 C.Y. excavator	BCY	0.053	0.00	2.38	2.18	6.05
Riprap	Random broken stone, machine placed for slope protection	LCY	0.258	30.00	11.50	11.4	63.00
Basin grading	Fine grade, top of lagoon banks for compaction	MFS	0.533	0.00	23.50	24.50	63.00
Swales grading	Finishing grading slopes, gentle	SY	0.002	0.00	0.08	0.08	0.21
Herbicide	Water soluble, hydro spread, add for weed control	MSF	0.027	0.48	1.02	0.66	2.60
Mowing bioswale	Mowing brush, tractor with rotary mower, light density	MSF	0.364	0.00	18.40	16.85	46.50
Seeding and fertilizing	Hydro or air seeding for large areas, incl. seed and fertilizer	SY	0.003	0.43	0.12	0.08	0.74
Erosion blanket	Jute mesh, 100 SY per roll, 4' wide, stapled	SY	0.010	1.03	0.38	0.13	1.85
Excavation	Excavator, hydraulic, crawler mtd., 2 C.Y. cap.	BCY	0.012	0.00	0.54	0.89	1.81
Underdrain trench excavation	Excavate drainage trench, 2' wide, 2' deep	CY	0.178	0.00	7.85	4.05	16.40
Backfilling with sand	Backfill trench, F.E. loader, wheel mtd, 1 C.Y. bucket, 100' haul; dead or bank sand	LCY	0.060	17.85	2.78	1.50	23.70
Vibrating plate compacting	Riding, vibrating roller, 8" lifts, 2 passes	ECY	0.003	0.00	0.14	0.13	0.36
Geotextile fabric	Geotextile fabric, woven, 200 lb. tensile strength	SY	0.006	1.90	0.24	0.00	2.46
Topsoil placement	Furnish and place, truck dumped, screened, 6" deep	SY	0.015	4.40	0.68	0.46	6.40

Table D1 (continued): General Activities Productivity and Cost (RS Means)

Construction/Maintenance Activity	RS Means Activity Name	Unit	Productivity (hours/unit)	Material ($)	Labor ($)	Equipment ($)	Total with O&P ($)
Curb and gutter	Forms and concrete complete, machine formed, 6" x 18", straight	LF	0.024	3.52	0.99	0.50	5.95
Headwall placement	Lightweight concrete channel slab, short pieces, 2-3/4" thick	each	0.060	1171.70	260.99	76.28	1778.23
Bioswale plug plants	Helictotrichon sempervirens, (Blue Oat Grass), Z4, cont., 2 gal.	each	N/A	14.65	0.00	0.00	16.10
Catch basin	Curb inlet frame, grate, and curb box, Large 24" x 36" heavy duty	each	12.000	520.00	520.00	0.00	1350.00
Manhole	Storm drainage manholes, precast, 4' I.D., 4' deep	each	7.317	725.00	320.00	50.50	1350.00
Manhole top	Storm drainage manholes, slab tops, precast, 8" thick, 4' diameter manhole	each	3.000	252.00	124.00	45.50	515.00
Mowing grass	Riding mower, 36" - 44"	MFS	0.027	0.00	1.30	0.88	2.94
Backfilling with excavated material	Backfill trench, F.E. loader, wheel mtd, 1 C.Y. bucket, 100' haul; dead or bank sand	LCY	0.060	0.00	2.78	1.50	5.85

Table D2: Reinforced Concrete Pipe (RCP) Productivity and Cost by Diameter (RS Means)

Diameter (in)	Productivity (hours/LF)	Material ($/LF)	Labor ($/LF)	Equipment ($/LF)	Total with O&P ($/LF)
12	0.320	11.00	12.75	2.43	34.50
15	0.320	14.00	12.75	2.43	37.50
18	0.364	18.00	14.45	2.76	45.00
21	0.400	22.00	15.90	3.04	52.00
24	0.480	26.00	19.10	3.64	62.00
27	0.609	37.00	25.00	8.00	87.50
30	0.636	42.00	26.00	8.35	95.00
36	0.778	56.00	32.00	10.25	122.00
42	0.778	75.00	32.00	15.65	149.00
48	0.875	89.00	36.00	17.60	172.00
60	1.167	136.00	48.00	23.50	249.00
72	1.400	206.00	57.50	28.00	345.00
84	1.750	275.00	71.50	35.50	455.00
96	2.333	330.00	95.50	47.00	565.00

Table D3: Culvert Headwall Productivity and Cost by Diameter (RS Means)

Diameter (in)	Productivity (hours/LF)	Material ($/LF)	Labor ($/LF)	Equipment ($/LF)	Total with O&P ($/LF)
15	0.343	2.00	0.00	272.00	274.00
18	0.384	142.00	0.00	385.00	527.00
24	0.425	423.00	0.00	610.00	1033.00
30	0.480	755.00	0.00	880.00	1635.00
36	0.436	970.00	0.00	1050.00	2020.00
42	0.600	1225.00	0.00	1250.00	2475.00
48	0.480	1500.00	0.00	1475.00	2975.00
60	0.716	2150.00	0.00	2000.00	4150.00

Table D4: Storm Sewer Cleaning Productivity and Cost by Diameter (RS Means)

Diameter (in)	Productivity (hours/LF)	Material ($/LF)	Labor ($/LF)	Equipment ($/LF)	Total with O&P ($/LF)
12	0.049	-	-	3.39	3.90
15	0.057	-	-	3.98	4.59
18	0.057	-	-	3.98	4.59
21	0.057	-	-	3.98	4.59
24	0.057	-	-	3.98	4.59
27	0.083	-	-	5.80	6.65
30	0.083	-	-	5.80	6.65
36	0.097	-	-	6.75	7.75
42	0.111	-	-	7.70	8.85
48	0.111	-	-	7.70	8.85
60	0.124	-	-	8.70	9.95
72	0.139	-	-	9.65	11.10
84	0.139	-	-	9.65	11.10
96	0.139	-	-	9.65	11.10

Table D5: HDPE Productivity and Cost by Diameter

Diameter (in)	Productivity (hours/LF)	Material ($/LF)	Labor ($/LF)	Equipment ($/LF)	Total with O&P ($/LF)
6	N/A (placed by hand)	1.90	2.52	0.00	5.95
8	N/A (placed by hand)	3.98	2.65	0.00	8.45

Appendix E – Results by Drainage Component

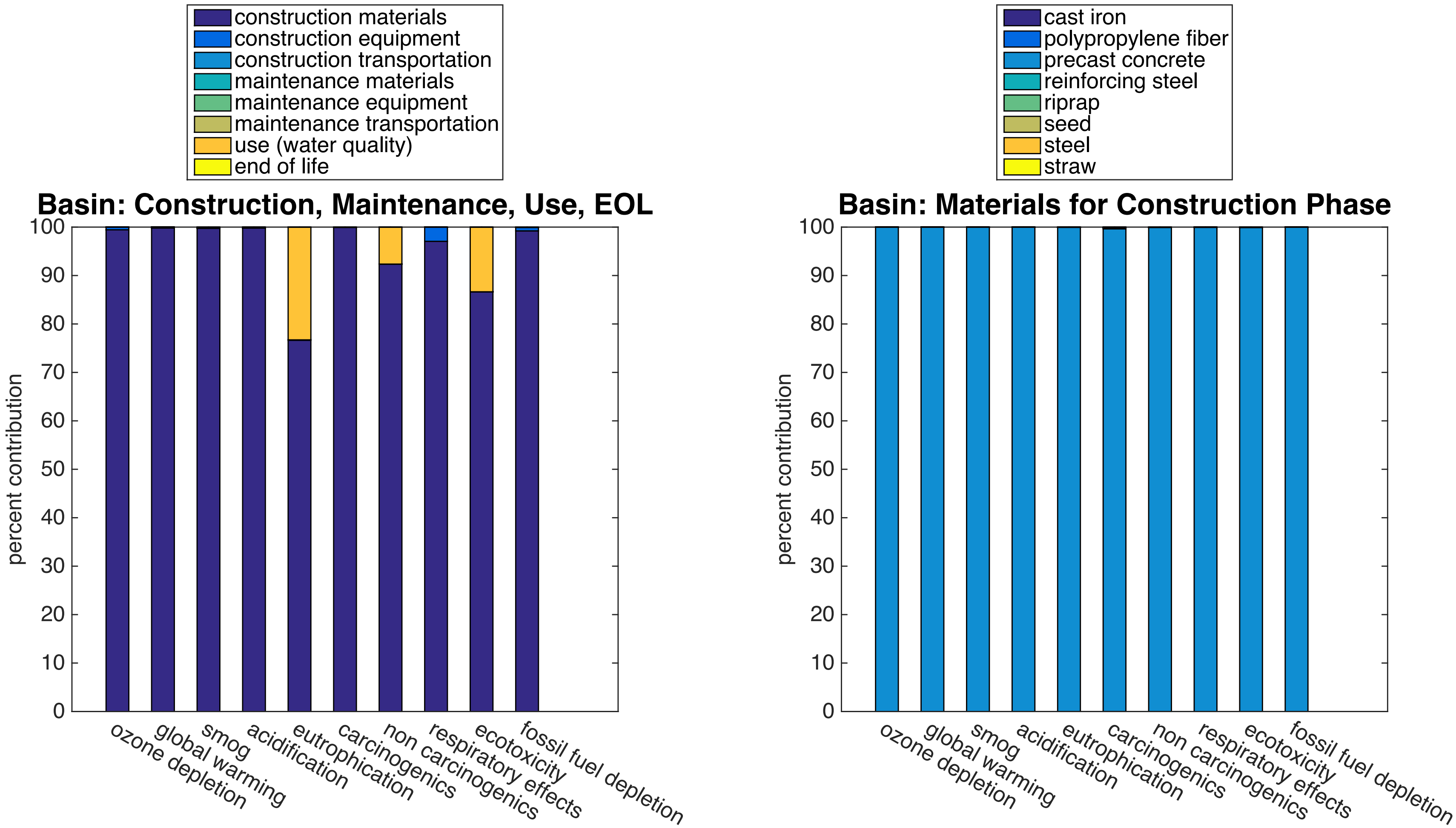
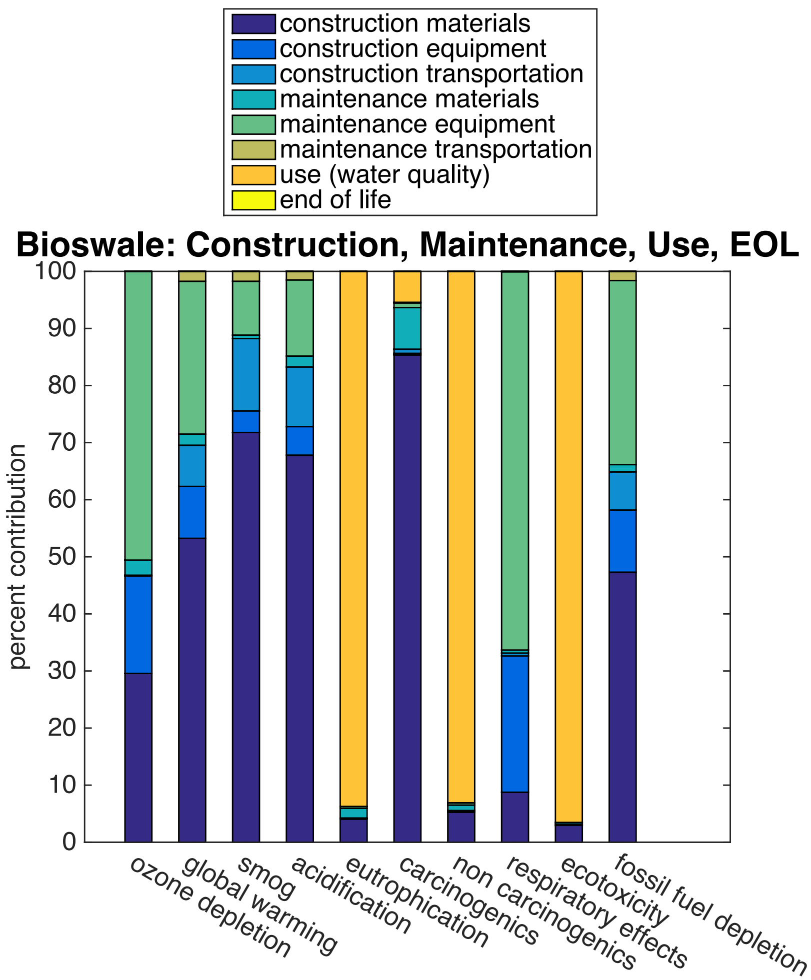


Figure E1: Basin Median Contributions of Life Cycle Phases and Construction Materials



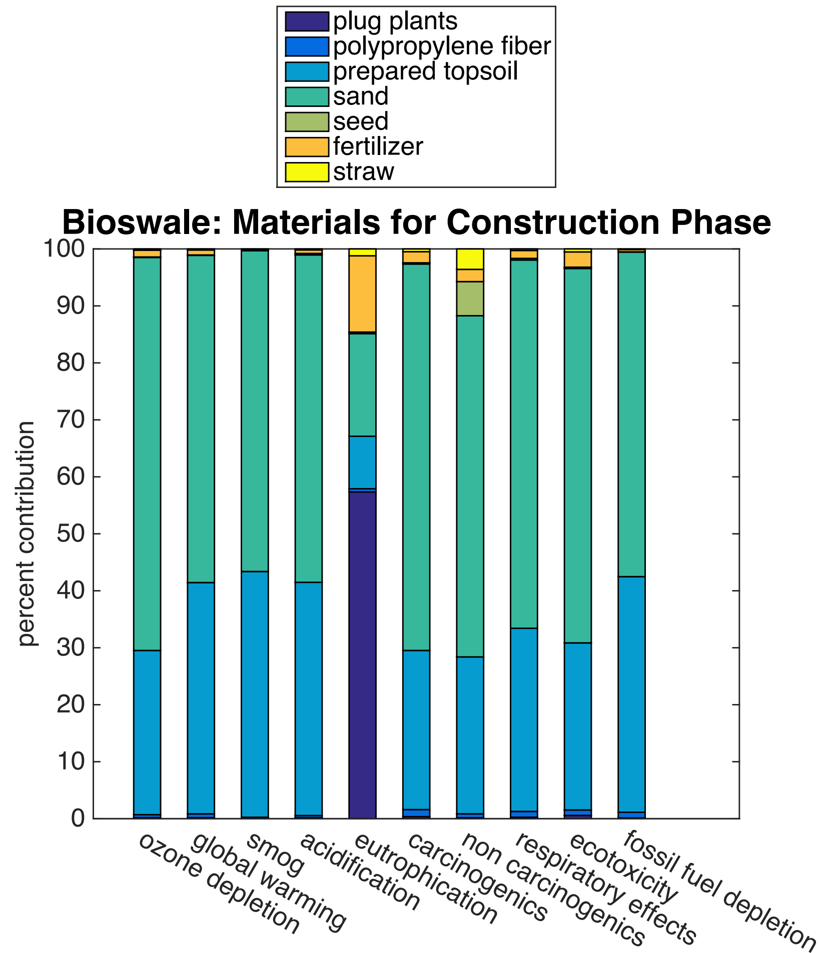


Figure E2: Bioswale Median Contributions of Life Cycle Phases and Construction Materials

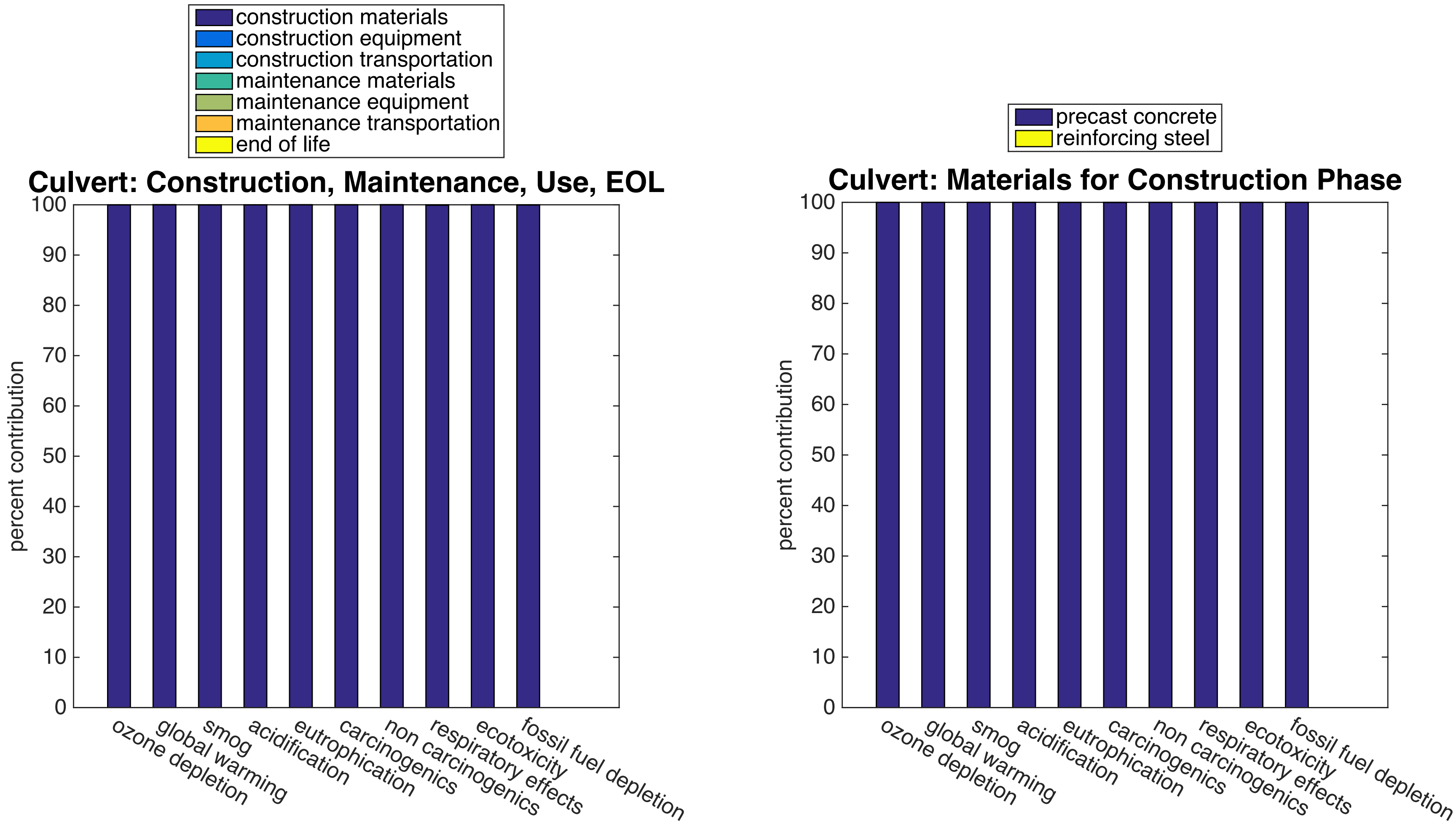


Figure E3: Culvert Median Contributions of Life Cycle Phases and Construction Materials

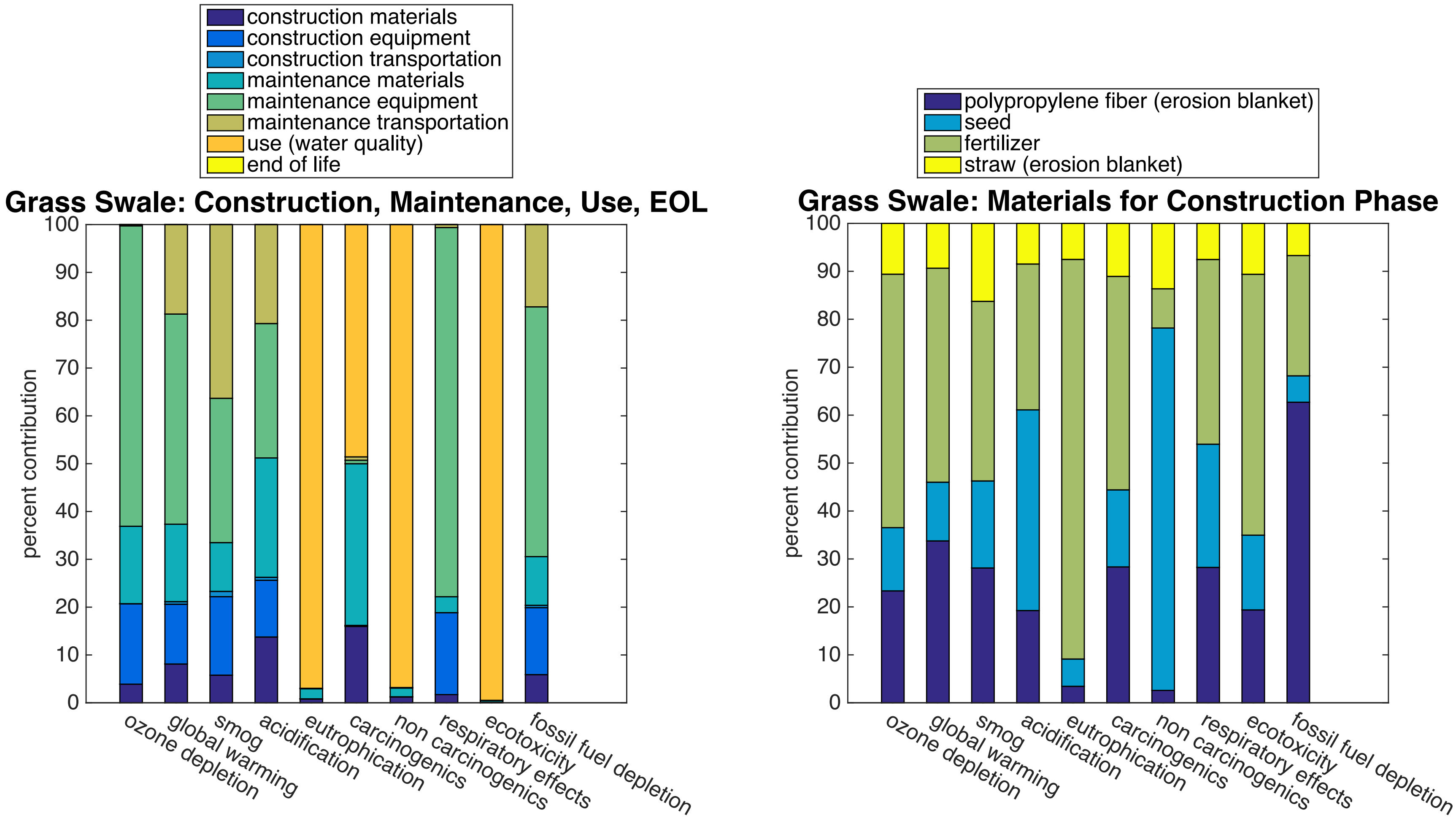


Figure E4: Grass Swale Median Contributions of Life Cycle Phases and Construction Materials

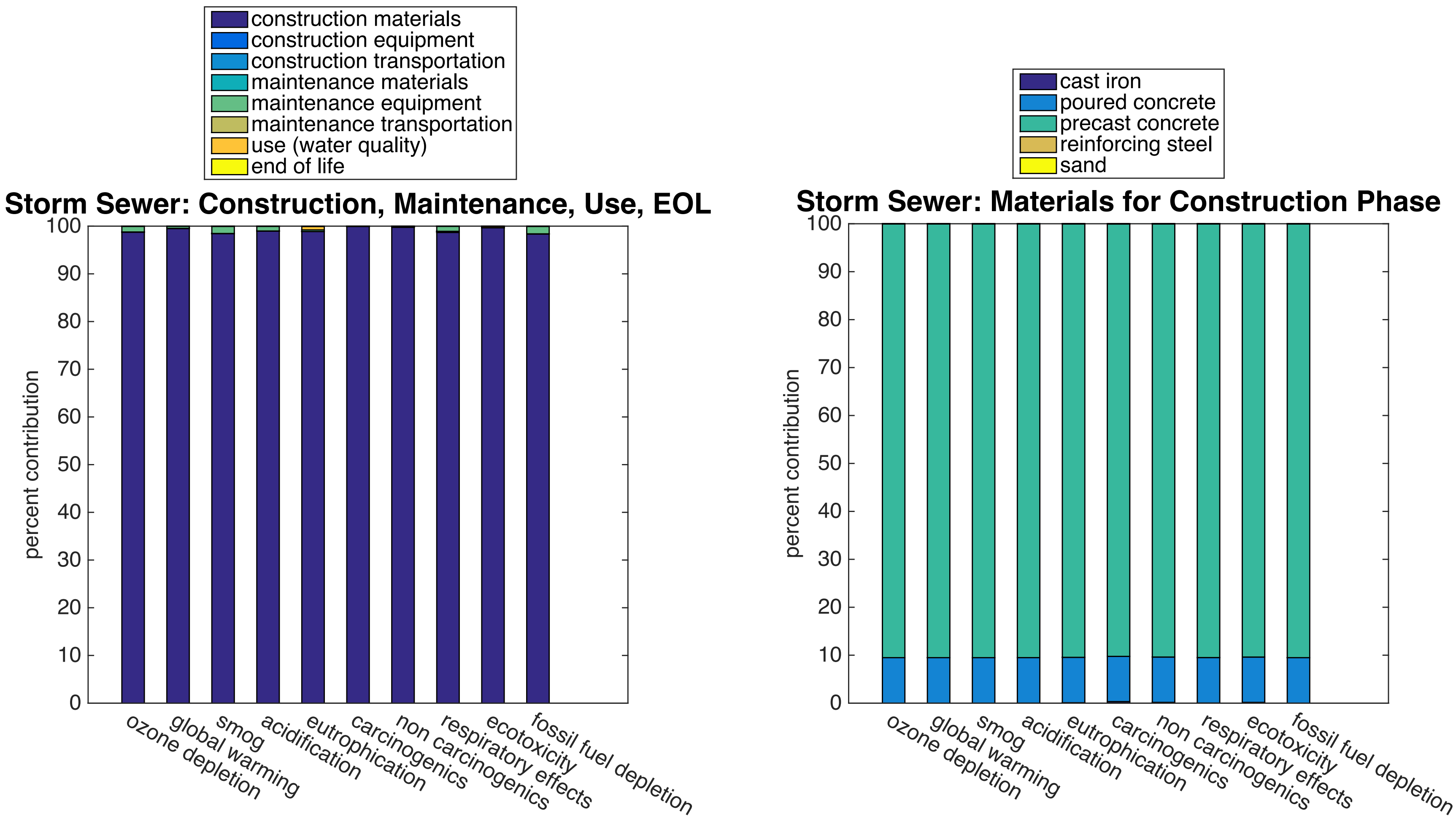


Figure E5: Storm Sewer Median Contributions of Life Cycle Phases and Construction Materials

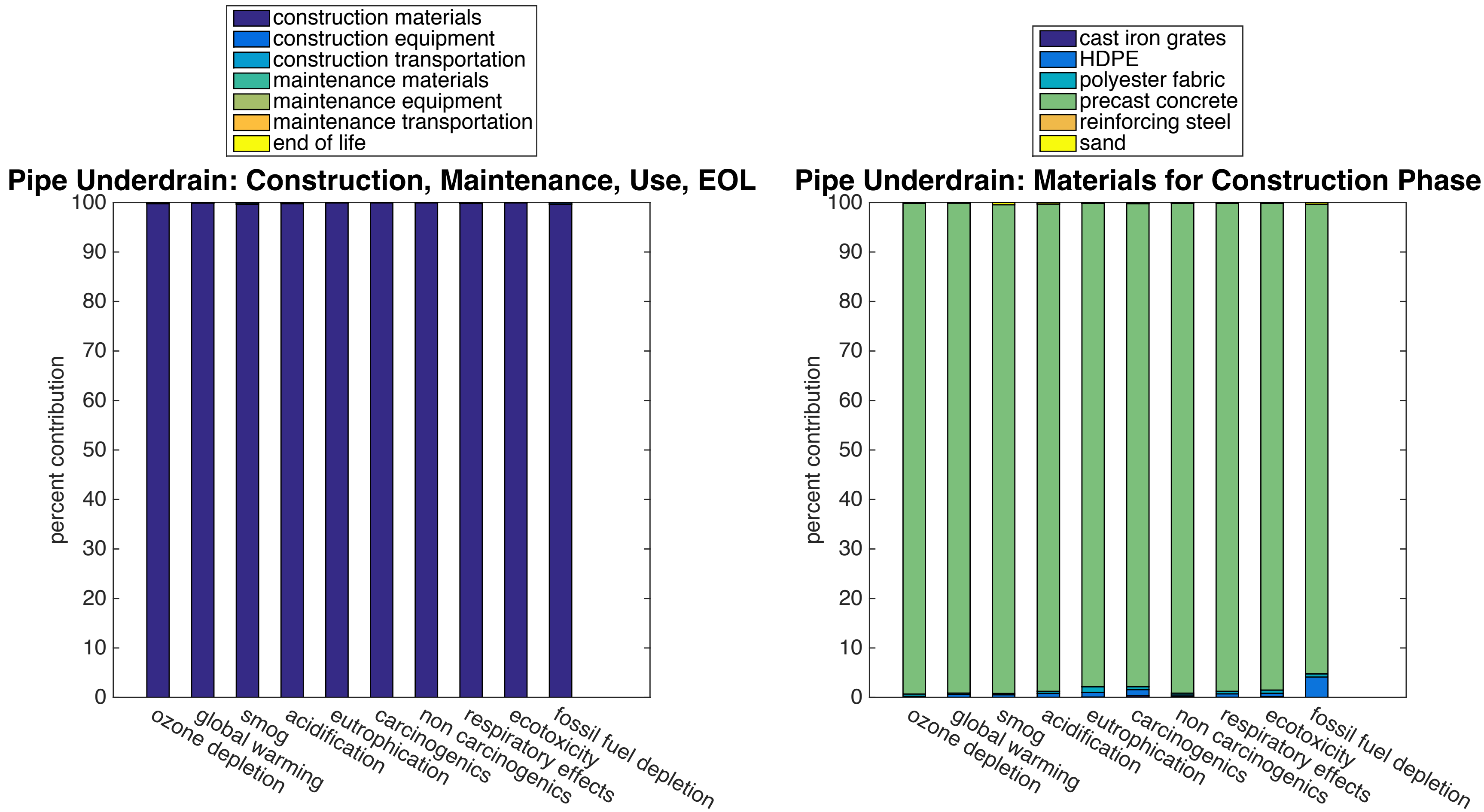


Figure E6: Pipe Underdrain Median Contributions of Life Cycle Phases and Construction Materials